PROCEEDINGS OF THE ROYAL INSTITUTION OF GREAT BRITAIN

Vol. 38 Part II No. 171
1960

Containing accounts of the
FRIDAY EVENING DISCOURSES
and other meetings

21 ALBEMARLE STREET LONDON W1

Price: 8s. 6d. per issue or 21s. per annum

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ON BOMBARDING SOLIDS WITH NEUTRONS

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Weekly Evening Meeting, Friday, 13th March, 1959

Sir Alfred Egerton, M.A., D.Sc., F.R.S.
Vice-President, in the Chair

THE MATERIAL world is made up from about 100 elements and the smallest unit of each of these elements which still retains the properties and characteristics of an element is the atom. The concept of the atom first originated in the Greek School of Democritus, but this early concept was crude, an atom of a particular element consisting of a small ball (Fig. 1(a)) which had definite chemical and physical characteristics peculiar to that element; in some mysterious and unspecified way, each atom retained its separate identity and characteristics.

In the late 19th and early 20th centuries a complex atomic structure of still smaller and more elementary units was revealed. These units were arranged in the atom in the form of a miniature solar system (Fig. 1(b)). The sun was still represented by a small ball (the nucleus) which was positively charged and which accounted for the mass of the atom. The nucleus, which varied in charge and mass between different elements, itself had a rudimentary ill-defined structure of elementary charged particles called protons. The number of protons in the nucleus decided what the element was and hence its characteristics. Around the nucleus revolved a number of much lighter elementary planetary particles—electrons—which were negatively charged. These electrons exactly balanced in number the positively charged particles of the nucleus. Each electron had its own orbit which could be circular or elliptical. The electron planets differed from their corresponding analogues in the solar system in that the electrons could jump from one orbit to another, although to a definite set of rules.

In 1932 Sir James Chadwick discovered the neutron. This particle had no electrical charge, it weighed a little more than the proton and it was a constituent of all nuclei with the exception of the hydrogen atom. Fig. 1 (c) shows that the nucleus, a

positively charged blob in Fig. 1(b), itself has a more clearly defined structure consisting of roughly equal numbers of neutrons and protons, the heavier elements having more neutrons than protons. In more recent times still other particles have been identified as the cement which may be binding the nucleus together; there are new particles, mesons, with a mass lying somewhere between that of electron and proton and which are either

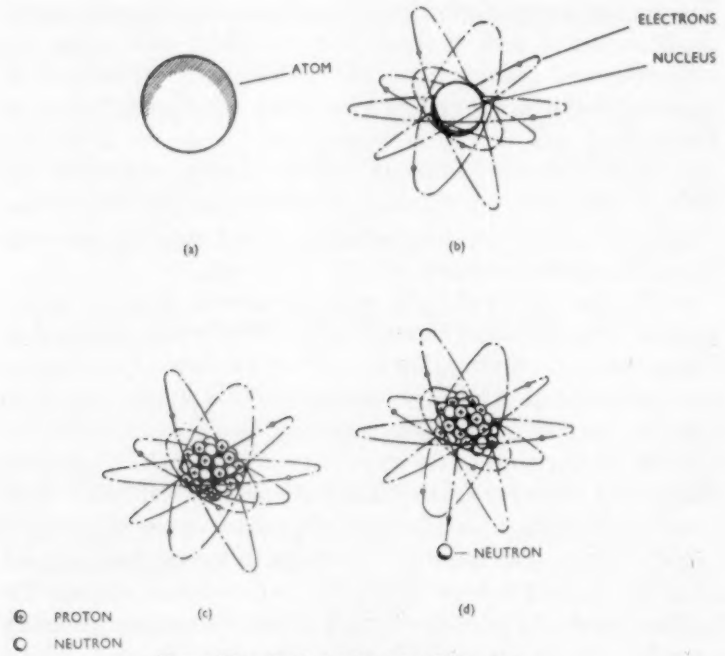


FIG. 1 Developing concepts of the atom.

positively or negatively charged or neutral; hyperons, which may also be charged or neutral and with masses greater than that of the neutron and proton and the most mysterious particle of all, the neutrino, with no mass and no charge. Here, however, we are only concerned with one of these elementary particles of nature—the neutron.

In nature, neutrons can be chipped off the nuclei of atoms when these nuclei are bombarded either by energetic cosmic rays or by particles ejected from naturally-occurring radioactive materials

(Fig. 1(d)). The number of such neutrons formed is comparatively small under these conditions, however, and machines (cyclotrons, synchrotrons and linear accelerators) have been built which speed-up alpha particles (i.e. positively charged helium atoms) to enormous velocities and then project these energetic bullets at targets to rip out neutrons from the nuclei of atoms. These machines provide larger quantities of neutrons than does nature unhelped but it is the discovery of fission which has revolutionised the industrial production of neutrons.

In fission the nucleus of a uranium (or a plutonium) atom is entered by a fast or slow moving neutron, thus upsetting the stability of the nucleus so that it breaks up into two new nuclei (or atoms) and more than two neutrons. This split or fission of the uranium nucleus is accompanied by the release of very considerable amounts of energy and it is with the latter that industrial nuclear power production is concerned. In this discourse we are interested in the fact that fission is accompanied by the release of *more than two neutrons*. We started just before fission with one neutron outside the struck nucleus; after fission we are left with more neutrons outside the nucleus than we started with. The vast supplies of neutrons available to scientists can be gauged from the fact that a modern nuclear research reactor can generate between 10^{13} and 10^{14} neutrons per sq.cm. per second.

The time between conception and birth of the neutron on fission is 10^{-14} second although a few take between 100 and 1,000,000 times longer, which is still not very long. At birth the neutrons are moving with a speed of about 45 million miles per hour (although they do not go for an hour at that speed). The free neutron has a half life of about 13 mins. This means that if one could hold a thousand of them in one's hand for 13 mins. and count them up after that, one would find oneself left with only 500; and if one held these 500 for another 13 mins. and counted them again, there would be only 250; and if one repeated this for a further 13 mins. only 125 would be there. The free neutron is thus not a stable particle; it breaks up, in fact, into a proton and an electron. Actually, the free neutron does not remain free for as long as 13 minutes since in the world in which it lives it meets and interacts with other matter in about 10^{-4} sec. When it is part of an atom the neutron does not ex-

hibit this decay characteristic. The neutron is, of course, smaller than the atom of which it forms a part; if placed side by side there would be roughly 10^8 atoms to every inch but 10^{12} neutrons could be fitted in this distance.

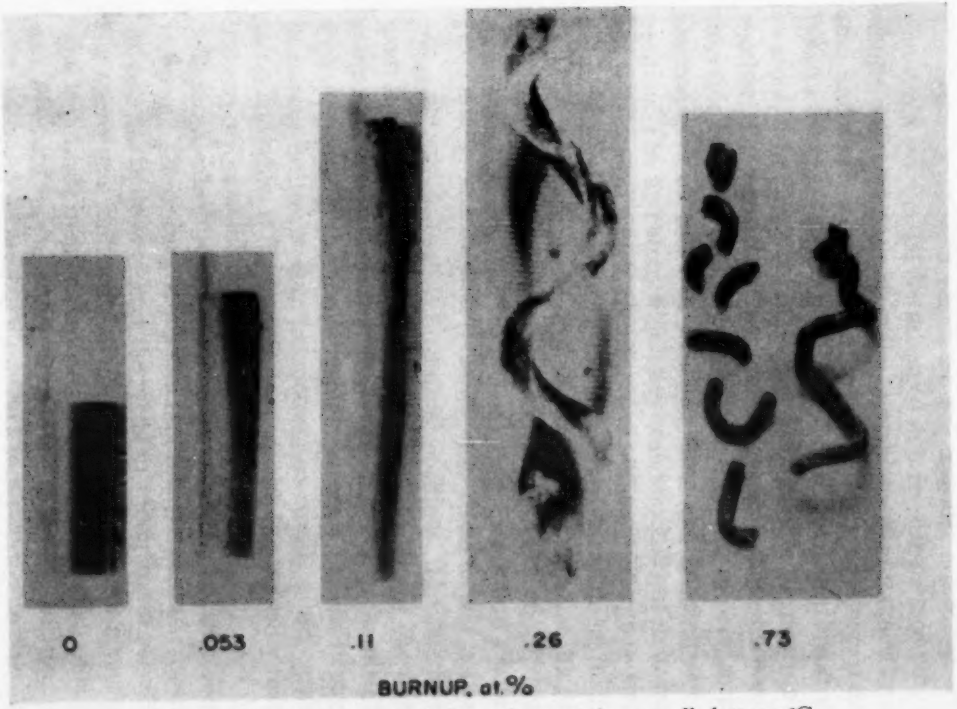
The effect of neutron damage through fission of Uranium

To illustrate some of the effects neutrons have on matter, there is no better place to start than to show some of the indirect havoc resulting from their birth on fission of uranium. Uranium metal, like all metals, is made up of a number of interlocking grains. Within each grain the atoms are arranged in a certain pattern, the differences between grains residing only in the relative orientation of these patterns to one another. In uranium metal, the crystal does not have the same properties in all directions; if, for example, a single crystal of uranium is heated and its expansion measured in three directions at right angles to each other, in two directions it would expand like a normal metal but in the third direction it would contract. These differences in properties in the three directions reflect also in differences in behaviour on irradiation. In one crystal direction (that in which the atomic distances contract on heating) the atoms in uranium metal move further apart on irradiation and the crystal grows; in a second direction the atoms move closer to one another and in that direction the crystal contracts; and in the third direction, the lattice stays put.

If the uranium is not properly fabricated and treated before it enters a reactor and if the metal is kept cool while it is in the reactor, then a bar will grow, distort and the surface wrinkle as shown in Plate I. If the process goes on long enough, the uranium will ultimately fracture. This phenomenon of growth applies only when the uranium is kept cool in the reactor (say less than 400°C). If it is above 450°C during fission, then a quite different state of affair occurs; fission then results in swelling of the uranium in all directions as shown in Plate II; a piece of uranium undergoing fission above 450°C may swell to four or five times its original volume.

The effect of neutron damage on metals

The neutrons themselves are not the direct but the indirect cause of these changes in uranium; in fact, it is the fission frag-

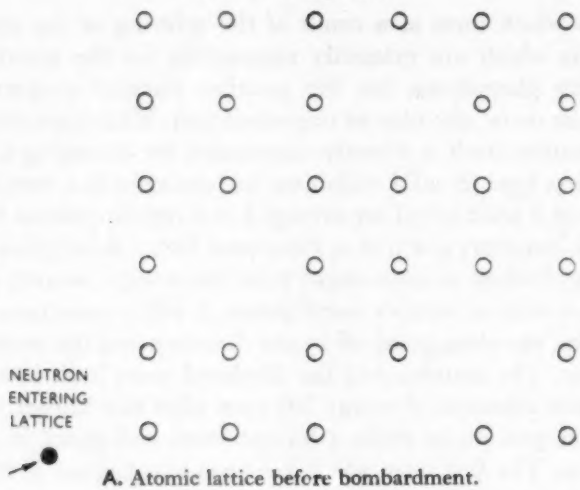


Effects of irradiation on typical uranium specimens rolled at 300°C.

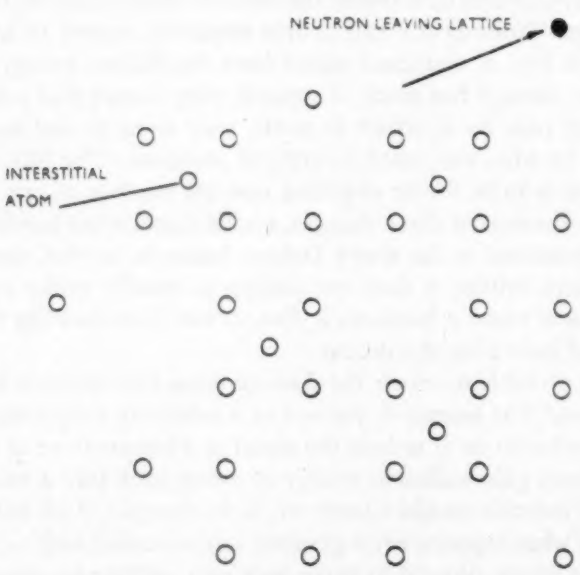
PLATE I

ments which form as a result of the splitting of the uranium nucleus which are primarily responsible for the growth and swelling phenomena but the peculiar physical properties of uranium metal also play an important part. What happens when the neutron itself is directly responsible for damaging a solid? The first type of solid which we will consider is a metal. The atoms in a solid metal are arranged in a regular pattern but, in nature, not every position in the crystal lattice is occupied by an atom and where an atom ought to be but is not, a vacancy is left. When a neutron enters a metal lattice, it will at some time strike an atom, the atom going off in one direction and the neutron in another. The neutron and the displaced atom both have considerable amounts of energy left even after this impact, so the neutron goes on to strike a further atom and knock it out of position. The first atom which has been knocked out in its turn hits other atoms which, in turn, have sufficient energy to strike third, fourth and fifth atoms, the neutron itself still doing further damage. Towards the end of this sequence, shown in its final form in Fig. 2, displaced atoms have insufficient energy to do further damage but since, in general, they cannot find a hole or vacancy near by in which to settle, they come to rest between atoms in what are called interstitial positions. The fate of the neutron is to be finally absorbed into the nucleus of one of the atoms. Because of these changes, a solid metal when bombarded with neutrons in the above fashion becomes harder, stronger, and more brittle; it does not deform so readily under applied stress and when it fractures it does so with less ductility than it showed before bombardment.

Is it possible to repair the damage caused by neutron bombardment? The answer is yes and in a relatively simple manner. All one has to do is to heat the metal to a temperature at which the atoms gain sufficient energy to move back into a vacancy. The Windscale incident however, is an example, if an unhappy one, of what happens when graphite is bombarded with neutrons and the atoms allowed to move back into position on annealing. If this annealing gets out of control, the disturbed atoms release a large amount of energy; this results in heating (of the graphite in this case) to high temperatures with all the consequences which may derive from this.



A. Atomic lattice before bombardment.



B. Atomic lattice after bombardment.

FIG. 2 Two dimensional diagram of effect of neutron bombardment on an atomic lattice.

Neutron damage of other solids

Metals are only one kind of solid. There are other kinds in which the atoms, although still arranged in regular patterns or crystalline forms, are not held together in quite the same way. One of these groups consists of the inorganic compounds like alumina, silica and lime and in this category are gem stones. If one irradiates gem stones in a reactor they change colour although not always to one more aesthetically pleasing than the original. If a diamond is irradiated in a reactor it changes from the transparent through yellow to black. All that is happening is that, as before, the atoms are removed from the regular lattice positions by bombarding neutrons and come to rest in an interstitial or non-regular lattice position. In these irregular positions, light is absorbed or scattered giving colour effects. Again, diamond and other gem stones altered by irradiation can be restored to their original colour by heating to a temperature at which the atoms can move back into normal positions.

Just as striking is the effect of irradiation on organic materials. An example is polythene. Polythene has an organic molecule of varying size in which the carbon atoms are aligned in regular chains. To these carbon atoms are attached hydrogen atoms radiating from the carbon like spokes of a wheel. When polythene is irradiated with neutrons, the molecule is broken at a particular point—at which point is a matter of chance. Once the link is severed, it is not certain that the original links will be reformed during the period in which the molecules settle down again; in many cases the original links are not reformed, the end link perhaps joining up with the shattered link of an adjacent molecule. This form of cross linking, which small amounts of irradiation are capable of achieving, confers new properties on the material. It may, for example, change the melting point or the strength of the material. Thus polythene bottles would be a great convenience in hospitals, but it would not be possible to sterilise a polythene bottle by immersion in boiling water since it would soften. By irradiating the bottle slightly which raises its melting point, which does not affect other properties adversely and which does not make it dangerous to handle, one would be able to sterilise by conventional methods. The change in mechanical properties of polythene as a result of irradiation is such that small doses of

irradiation make it flexible whereas large doses make it stronger; the very largest doses make it quite brittle so that it behaves almost like a glass.

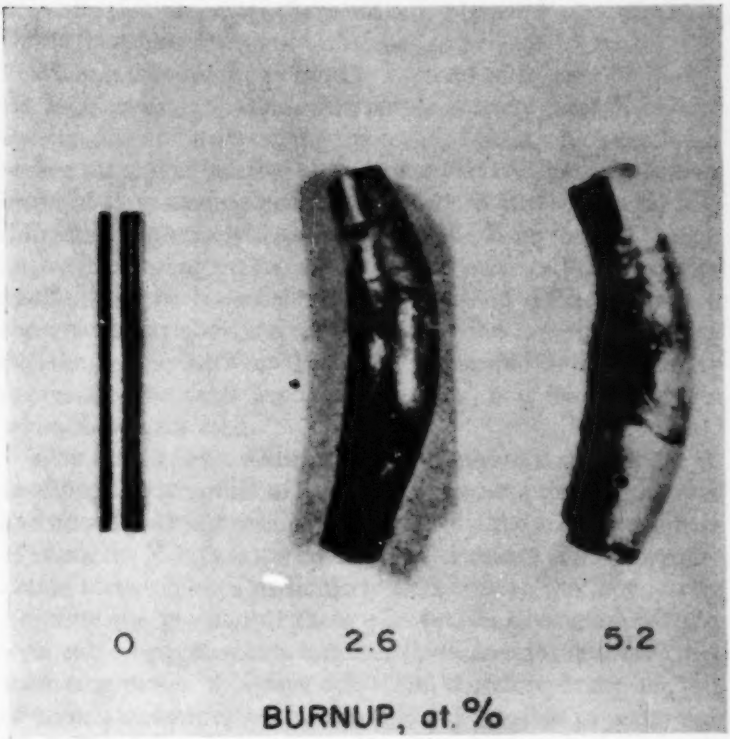
If these changes can be effected in polythene the possibilities of changing other organic materials are evident. One can conceive of modifying these properties either in the raw material stage before shaping it or by taking a material, moulding it to shape and then irradiating it. Whether one will ever see irradiated nylons which do not wear or collect dirt, or whether man will ever wear irradiated shirts which have a property or texture quite different from ordinary materials, remains to be seen. And this change in structure as a result of neutron bombardment applies not only to non-living matter but even to living matter. The effects of irradiation on seeds or plants produce interesting, unusual and even useful new types of vegetation.

The constructive aspects of neutron bombardment

(a) *Neutron diffraction*

So far we have dealt with the effects of neutrons on matter and the ways in which they can change this matter or affect its properties. Now I would like to consider the constructive rather than the "destructive" use of neutrons. Although neutrons at birth have very considerable energies and move at very great speed, it is possible to slow them down to a point at which they have insufficient energy to knock an atom out of its lattice position but merely bounce off it. To slow down a neutron one saps its energy by making it collide with light atoms to which it transfers its energy in the process without being absorbed into the nucleus. The elements which do this job of "moderation" most satisfactorily, are atoms like heavy hydrogen, beryllium and carbon. To slow down neutrons from fission energy to average energy at room temperature, the fission neutron requires to make 25 collisions with deuterium or about 100 with beryllium or about 120 with carbon.

These slow neutrons have two properties which make them particularly useful. The first is that, because they are not electrically charged, they have the ability to pass through the electron cloud surrounding atoms and reach the nuclei; the second property is concerned with the peculiarity of elementary particles



Effect of irradiation above 600°C on cast uranium alloy.

PLATE II

of nature that they can behave not only as particles but also have wave characteristics.

When a crystal of any kind is exposed to a beam of X-rays the regular array of atoms diffracts or scatters these X-rays in specific directions depending upon the angle at which the beam strikes the crystal relative to the atomic array. Similarly when a beam of slow moving neutrons is made to strike a crystal it is diffracted in precisely the same way as the X-rays and at certain angles (depending on the structure of the crystal) the intensity of the neutrons is concentrated. The law of diffraction which these neutrons obey and which enables the experimentalist to find the distance between the planes responsible for the scattering is precisely the same law (the Bragg law) as is found to obtain when X-rays are used.

Why bother with neutrons when X-rays are so effective in revealing the structure of matter? X-rays have their limitations and one of the most serious of these is that the scattering power of atoms for X-rays is not equal for all elements. The heavy elements scatter X-rays particularly efficiently so that one is able to locate the position of these elements in crystalline matter; with some light elements however (hydrogen for example), the scattering power of X-rays is low and therefore in the analysis of certain structures by X-rays it is not possible to determine where the hydrogen atoms are. However, hydrogen is extremely effective in scattering neutrons and can be located by neutron diffraction. Since hydrogen is one of the major components of a considerable number of inorganic and organic materials, this new technique is important in the elucidation of the atomic structure of a wide range of compounds.

As an example, neutron diffraction techniques have been used to determine if the water molecules in alum and copper sulphate were essential to the structures or were merely tacked on in odd positions where they were easily removable from the molecule. For alum it has been shown that the water molecules are an integral part of the structure, that they actually hold the molecule together and that if these water molecules are removed, the molecules as a whole tend to collapse. This can be demonstrated very simply by heating an alum crystal, thus driving off the water, whereupon the original crystal turns to powder.

When copper sulphate is heated, however, all the water molecules do not come off at once but do so in successive stages. The reason for this is that all the water molecules do not occupy equivalent positions in the lattice; furthermore, as the water molecules are lost successively, the other atoms readjust themselves to the remaining water molecules which hold the structure together.

Another application of neutron diffraction is to organic materials, like benzene, to locate by more direct observation than has been possible before, the position of the hydrogen atoms. This is important to the petrochemical industry whose starting point is the simple organic molecule from which the synthetic materials of today are built. The technique can even be used, because of the peculiarities of scattering diffraction of neutrons in their interaction with atomic nuclei, to determine such refined behaviour as the direction of spin of the nuclei in magnetic materials.

(b) *Isotopes*

We have now seen how neutrons can be used to knock atoms out of position or to bounce off them. Neutrons can also be captured by the nuclei of atoms. This capture process is responsible for the new isotope industry with its far reaching usages in science, particularly the biological sciences, and in industrial technology. In the nucleus there are protons and neutrons and the number of protons (which exactly equals the number of electrons) determines the chemical properties of the material. It is possible, however, to have associated with a given number of protons a variable number of neutrons. In such cases the chemical properties of the material are not changed, but its atomic weight is. Elements which have the same number of protons but different numbers of neutrons in the nucleus are called isotopes. To make an isotope of an element all we have to do is to get that element to absorb or lose a neutron.

Isotopes are made by introducing into the reactor, in suitable containers, materials which it is known will, either by capture of neutrons or by capturing neutrons and subsequent radioactive decay, give a particular isotope. The feature of these isotopes which has made them so useful is that many are unstable after

they are formed and the new nucleus decays or breaks up, in the process throwing out either an alpha particle (which is a positively charged helium atom), a beta particle (which is an electron), a gamma ray (which is a form of electro-magnetic radiation) and in some cases even a neutron. These particles which are emitted can be detected by a Geiger counter for instance and the presence of the parent atom revealed. The 'labelling' of compounds with a small number of unstable isotope atoms thus enables the movement of the atoms of the compound to be traced through a variety of processes and identified in the presence of other atoms of the same kind. This has led to very important advances in science.

Isotopes with higher radioactive intensities can be used instead of X-ray machines for radiography, for medical purposes such as the treatment of cancer, and for industrial purposes such as changing the properties of matter and the killing of virus or insect pests by dosing them with irradiation. This has all come about because it is possible for a neutron to enter the nucleus of atoms.

Perhaps the most striking of all the isotopes which a neutron can make is plutonium which does not exist naturally and only came into being with the realisation of atomic energy. It is formed from the non-fissile uranium isotope, uranium 238. In uranium 238 there are 92 protons and 146 neutrons. When a neutron enters the nucleus of uranium 238, it forms uranium 239 with 92 protons and 147 neutrons. This is unstable and breaks down first into neptunium which contains 93 protons and 146 neutrons and subsequently into plutonium which contains 94 protons and 145 neutrons. This plutonium is fissile and if now another slow neutron enters the plutonium nucleus, the latter can fission, breaking into two almost equal nuclei with the formation of two or more neutrons. So now we are virtually back to the beginning where I described how the neutron virtually breeds itself directly from uranium 235.

EXHIBITS IN THE LIBRARY

A display of fuel elements for nuclear reactors and stages in the manufacture of elements for the DIDO reactor; gemstones illustrating the effects of pile irradiation; examples of monitoring equipment; Bradwell spiral fuel element and specimens of rare earth elements; arranged by *Dr. H. M. Finniston* and and the *U.K. Atomic Energy Authority*.

ELECTRONIC "BRAINS"

By H. A. THOMAS, D.Sc., M.I.E.E., S.M.I.R.E.
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Weekly Evening Meeting, Friday 4th December, 1959

P. H. Schwarzschild,
Vice-President, in the Chair

THE ART of calculation has been studied for many thousands of years: some of the calculations of the ancients, for example, those which predicted eclipses of the sun, still command our admiration today.

The abacus, or counting frame, was invented thousands of years ago, and, in fact, the word "calculate" is derived from the pebbles or "calculi" which slid on the wires of this simple device.

Numerical work, which is usually thought to be tedious and uninteresting, has always been of immense importance to science and commerce. The oldest written "documents" produced 5,000 years ago in Mesopotamia on clay tablets were primitive books of accounts. Thousands of years later most of the earliest books published by the first printing press were text books of commercial arithmetic.

Nevertheless up to a few hundred years ago, the art of calculation was neither commonly understood nor widely practised. In 1662, for instance, Samuel Pepys, who was then in charge of the contracts branch of the Admiralty, found it necessary to rise at four o'clock in the morning to learn his multiplication tables. He had been to Cambridge; and was, by the standards of his time, a well-educated man, in later life becoming President of the Royal Society and a friend of Newton—but when at the Admiralty he found himself quite unable to understand the simple calculations which had to be done when buying timber for the King. In those days schoolboys seldom went beyond "two times two".

Since then, computation has become more widely understood as the need for it has grown, but, as Barlow remarked a hundred years ago, "Calculation is laborious and unremunerative" and, he added rather pathetically, "a moderate skill in computation and a persevering industry are not precisely the qualities

a mathematician is most anxious to be thought to possess."

The introduction of logarithms by Napier and Briggs revolutionised ordinary computing; our civilisation, dependent as it is on navigation, surveying, and astronomy, would never have developed as it has without them.

For centuries, inventors have devoted themselves to the development of calculating machines to reduce the drudgery of computation and improve the reliability of the results. As far back as 1671, Leibnitz, who invented the stepped wheel still used in some adding machines, said "It is unworthy of excellent men to lose hours like slaves in the labour of calculation which could safely be relegated to anyone else if machines were used."

Such calculating machines are of immense value; and we must now see how they can be used. Let us imagine, for example, how a girl would undertake a typical clerical calculation. Firstly some information arrives which we call the INPUT. The girl selects what she wants and writes it out, in other words she stores the information for use later on. Next she feeds each bit of information into a desk calculator and writes out each answer on a sheet of paper. When all the necessary steps have been completed she copies the answer on to another sheet which goes into the OUT tray. The girl herself is the control unit of the system, following a fixed sequence of instructions.

The parts of this human processing system are shown in Fig. 1: information enters through the input unit, is recorded in the storage or memory unit, transferred to the processing or arithmetic unit, returned to storage, and finally leaves through the output unit, a control unit directing the entire operation. If several different calculations have to be made, this procedure is repeated for each one.

Various attempts have been made to invent machines which can undertake a series of calculations and not just one at a time—machines capable, in fact, of obeying a whole set of instructions. Over a hundred years ago, for instance, Charles Babbage invented a mechanical device to do this: he devoted his life to making it, but the engineering skill of that time was unequal to the task and the machine was only partially constructed. Babbage's ideas have only been properly appreciated in the last twenty years, but we now realise that he understood quite clearly all the fundamen-

tal principles which are embodied in modern computers. His contemporaries marvelled at him, though few of them understood him; and it is only in the course of the last few years that his dreams have come true.

In 1812, looking at a table of logarithms, which he knew to be full of mistakes, he conceived the idea of computing tabular functions by machinery.

He proposed using his machine both for computing new tables and for checking those which had already been published: he constructed a small working model in 1822, which was received with such enthusiasm that he contemplated making a much larger machine, working to twenty decimal places. The Royal Society supported this project and Babbage had an interview with the Chancellor of the Exchequer who promised to arrange a subsidy to pay for part of the development. The Government built him a workshop and a special fireproof vault to house the vast number of drawings which he was preparing, but Babbage took much longer than he had anticipated and in 1842 official support was withdrawn. The partly built machine was left in Somerset House until it was demonstrated at the International Exhibition of 1862, where it excited great interest, but poor Babbage had to give almost all the demonstrations himself, and many people were unable to see it. Babbage then had more trouble with the Government, and finally all further development was abandoned.

Babbage was misunderstood by his contemporaries, and quarrelled with most of them; he became estranged from almost all his friends and finally became an embittered old man. He felt himself completely out of sympathy with his contemporaries and, like many other inventors both before and since, he was quite unable to cope with Government Departments.

Poor man, he tried to solve by himself and with his own resources a series of problems which in the end taxed the united efforts of thousands of engineers over a quarter of a century. Let us, who can assess his achievements more accurately, think rather of his foresight, his imagination and his courage.

The main problem in getting any calculating machine to work quickly enough is the construction of a suitable memory into which numbers can be inserted, retained, got out, and erased

all in a fraction of a second. Mechanical systems involving peg memories have been used: peg combinations representing each number are set up by sliding rods and retained until required, electrical relays have been used successfully and so have electrical switch and uniselector contact systems. But not until the electronic developments of the last war period was it possible

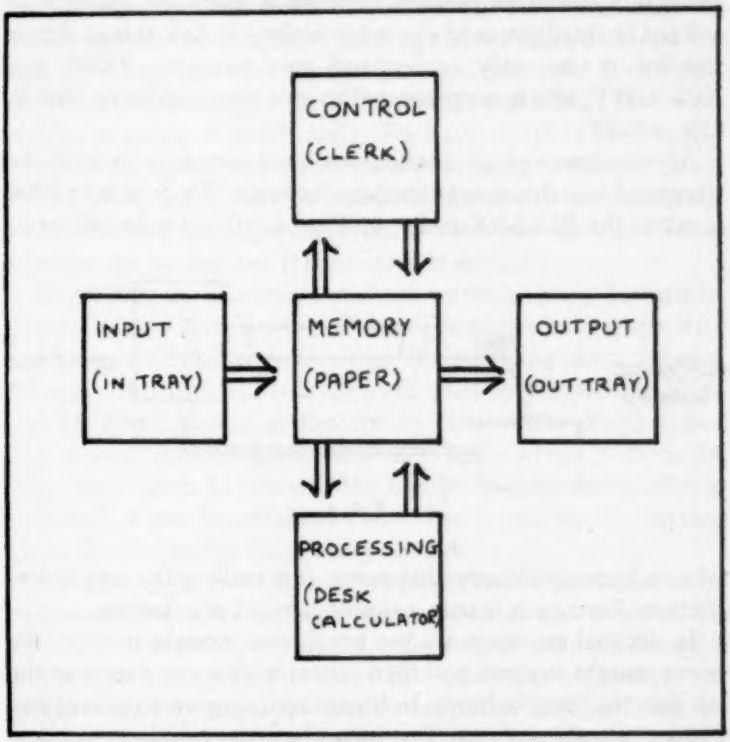


FIG. 1

to achieve adequate speed—speeds of millions a second in fact, made possible by the ability of electronic valves to act as high-speed switches.

Thus was born the electronic computer. It consists essentially of an input unit to put the numbers in, a memory to store the numbers, a processing or calculating unit to do the arithmetic, an output unit to translate the machine language back to human language, and a unit to control the whole series of operations.

The numbers go from the input to the processing unit via the memory, then back to the memory and finally out—all under the supervision of the control unit.

The similarity with a human being is obvious (Fig. 1) because of this similarity the machine is often referred to as a "brain". Let me disillusion you right away—although clever people can make such machines perform remarkable tasks, the machine itself has an intelligence of a very low order—in fact, it is so simple minded it can only understand two numbers, ONE and NOUGHT, which are presented to it in electrical form, that is, ON or OFF.

All numbers and all instructions must somehow or other be translated into this simple machine language. We do this by what is called the BINARY code—and we do all our calculations in

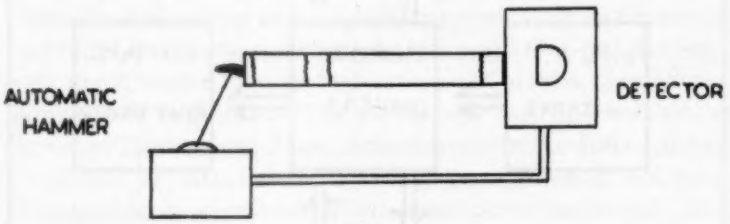


FIG. 2

what is known as binary arithmetic. It is really quite easy to understand because it is only a simple method of counting.

In decimal counting, we use ten figures, nought to nine. We count nought to nine, and then repeat with a carry-over to the left into the 'tens' column. In binary counting we only have two figures, nought and one. Just as in decimal counting, we carry over to the left every time the figure changes to nought. But this time each carry-over only doubles the number instead of multiplying it by ten. Five switches, representing the decimal numbers 1, 2, 4, 8, and 16 can make any number up to their sum, i.e. 31. A sixth switch would add 32, a seventh 64 and so on. To make up to 1000 for instance, ten switches would be needed and, up to a million, twenty switches.

In an electronic computer, numbers, expressed in this code, are built up as a series of impulses: I will explain soon how this

is done, but first would like to show you how a number made up of ones and noughts can be stored and so memorised.

Consider a metal rod which can be struck a blow with a hammer. Each time the hammer strikes the rod a shock wave travels from left to right (Fig. 2). If a series of blows is struck, representing a number in binary form, the series will travel along the rod. Let us now introduce at the end of the rod a wave detector 'D' which operates an automatic hammer. Now, when we strike the rod, each time the wave reaches the right-hand end it will produce, instantaneously, a strike at the left-hand end. The wave will be maintained indefinitely. We have in effect, a memory. Let us start again with a new binary number. This will be retained while the circuit is closed. If the circuit is opened the number is lost—in other words the memory is erased, and a new number can be inserted if the circuit is restored.

In practice the succession of shock waves is inserted by a coil, down a nickel wire inside a sleeve. They travel along the wire and are picked up by another coil. After passing along the wire the wave is deformed. It is then accepted by the pick-up valve and amplified, passed to the middle valve for re-shaping, and then passed back to the driving valve again where it starts the wave once more. In this way the number can be stored till it is required: it can be obtained every time it reaches the driving valve, that is, 30,000 times every second.

We now begin to see how a computer works. An actual computer contains many memory stores, switches and circuits. To show how it works, I will take the elements of a typical machine and the very simplest job it can do—adding two numbers together—say 179 and 294—and in very slow motion I will go through the sequence of operations which takes place in reality in less than a thousandth of a second. If we can understand how it can add we are a long way to understanding its working, because the operations of subtraction, multiplication and division can all be performed as additions.

Firstly, we write out the instructions to be obeyed and the numbers to be used—this information is punched onto paper tape, that is, we convert it into machine code language. The tape which would have had to be punched to do our addition sum consists of five groups of holes, the first three groups are coded

instructions in binary form which operate various switches, the second two represent in binary form the numbers to be added together.

The basic elements of the machine are shown in Plate I. They are, firstly, the Memory—as I have described previously this is merely a wire down which vibrations started at one end will travel to the other end, automatically be returned and so 'memorised'. Then there is another smaller memory, 'S', which is only one sixth of the length of the big memory: there is an electronic device called the 'Adder' which, if two numbers go into it, can add them and present the sum to the little store S: there are a lot of electronic switches which are controlled by the instruction unit marked "INS"—the particular switches which are closed are dependent upon coded instructions which enter through the input compiler by way of an input reader which reads the punched tape. There is a Master Gate, which always closes for precisely one of the six equal periods controlled by the master Clock: and lastly there is the output compiler, connected to the output punch which punches out the answer onto paper tape.

The first step is to put the input tape into the reader. As it runs in, each combination of holes in the first instruction closes corresponding switches and the whole four combinations will be added up or compiled to set up a composite number, or the first instruction, on the input compiler. A switch, rotating at six times the speed of the master Clock, scans this combination and produces a corresponding pattern of impulses which can be passed into any part of the machine by first closing appropriate switches and then closing the master gate for one of the six periods of the master Clock.

If the gate is closed at time 1 on the master clock the first instruction will go into the corresponding part of the memory. If then closed at time 2, the second instruction will be passed into an adjacent block in the memory. If the gate is closed at time 3, the third instruction will be put in the memory, followed at times 4 and 5 by the first and second number. The three instructions and both numbers are thus circulating in the memory as adjacent blocks or patterns of pulses: the machine is ready to start work.

Now, what would happen in the next thousandth of a second

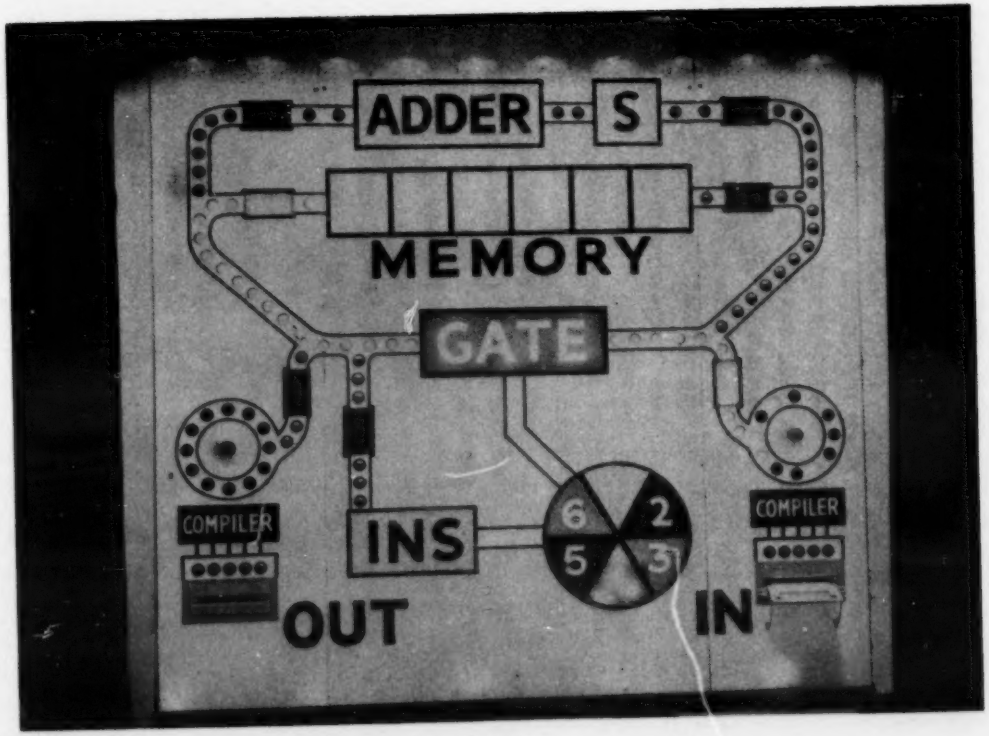


PLATE I

is this. After the appropriate switches are closed the gate closes at time 1 so passing the first instruction to the Instruction unit: this instruction sets up two switches and at time 4 closes the gate so passing the first number into the little store S. Then, at time 2, the second instruction is passed to the Instruction unit: this instruction closes the appropriate switches and at time 5 closes the gate so passing the second number through the adder into store S. The two numbers, originally in positions 4 and 5 in the memory have now been passed through the adder into store S. The addition has been done. The answer is already there in store S.

To obtain the answer we must obey the third instruction which is in position 3 in the memory. The gate is closed at time 3 and the third instruction passed to the Instruction unit; this sets up two switches, closes the gate and passes the answer out to the output compiler where it is set up in binary form. All that remains to be done is to start the output punch and the answer will be punched out on paper tape. If this tape is fed into a reader which automatically works an electric typewriter, the answer will be printed out on ordinary paper.

All this may seem to you like using a sledge hammer to crack a nut—of course it is, if you were doing only this one simple addition; but if you had to do hundreds of thousands with ten-figure numbers it would be well worth while, because each addition would only take a thousandth of a second. With a pencil and paper it would take 25 minutes to do this sum:

$$\frac{6543972108 \times 3497412167 \times 1429864731}{3498621041 \times 9864100231 \times 4187643209}$$

a desk calculator could improve the time to 1 minute: but an electronic computer could do it in 1/100 second.

In a large machine about 5,000 figures can be stored in the nickel wire memories; another 150,000 figures on a magnetically coated disc as magnetised dots which can be written in 30 thousandths of a second and erased just as quickly—the disc is equivalent, in fact, to our previous work sheet; lastly, 3 million figures can be stored on magnetic film. Information can be transferred from disc to film as required, worked on, sorted or erased; the film is like a huge ledger in which items can be inserted, altered, sorted, or erased at will.

The whole complex machine is under the control of one operator—once the instructions are put into the reader and the machine started, the whole series of calculations is entirely automatic. The speed of calculation is so fast, in fact, that most of the time is taken up in putting the information in and printing the answers out. Devices which can read documents directly by scanning with an electric eye, so avoiding punching paper tape by human beings, are now being developed, as are also ingenious machines which by entirely electronic means can print out at speeds of 5000 figures a second.

The computer was originally designed for scientific and technical work. It has been used in many departments of atomic energy research and in connection with such advanced scientific techniques as radio astronomy. It has been used in aeronautical research where a machine with a vast capacity for rapid mathematical calculation is essential; for example, it can tackle the complex problems of stability on new aircraft, the solving of which before taking the plane up may save lives. The facility of computers for storing great quantities of information has brought entirely new possibilities to such fields as air traffic control and weather forecasting.

In commerce, too, the amount of computation which has to be done these days seems to increase rapidly from year to year.

Today, an executive must have up-to-the-minute information on all aspects of his business; he must know all the facts about production, about sales, about stocks, about transport, staff and prices.

The organization of business gets more and more complicated: the modern state can only be run efficiently on a diet of facts; we are quickly becoming a nation of clerks and today nearly 11% of the working population spend their time putting these facts in order, choosing the right ones, copying them out, adding them up and typing them, stamping them, counting them, checking them, compiling them and filing them. But in spite of all this effort, there is never enough of the right information and only too often it goes In—Out—In—Out—In—Out—Pending.

A computer can obtain such vital information and present it quickly in a form best suited for management purposes. But it is not limited merely to doing arithmetic: one of its greatest attri-

butes is its ability to make judgements. Many practical problems involve decisions while a calculation is being made—choices in fact: the computer's system of ON/OFF switches can give 'Yes/No' answers as the calculation progresses and so it can itself decide at any point which of two paths to follow depending on an intermediate answer it has itself supplied.

This valuable ability can be illustrated by the working out of an employee's National Insurance contribution.

There are many rates, depending on many variables, but the computer can be programmed to work through a chain of choices —sick or well? male or female? over or under eighteen? married or single? and produce the week's rate for a particular employee. It follows through this kind of logical process under its own control.

Many large-scale commercial systems are of this basic type —and once broken down into successive 'Yes/No' stages can be handled by the computer.

The computer's startling capacity for mathematical calculation is finding new applications in many fields. For transport, it can work out the best of all the variations and combinations possible in moving different quantities of goods to and from different places in ever changing circumstances. In the factory itself, the computer can help to determine both its most economic size and even the best place to build it, calculating the relative importance of factors such as sources of raw materials, sources of suitable labour, access to main consumers, and distance to port facilities. In some factories there may be more than one way of using raw materials and plant. The computer can help us to know which is the most advantageous.

Again, it can bring a new accuracy to the calculation of production schedules. Planning normally starts with an estimated volume of sales; the problem is to produce the goods most economically.

Take labour for instance. Too much labour is wasteful—shortage of labour, made up by overtime, is expensive. Idle equipment is wasteful—but under-equipment may mean overworked machines and breakdowns. Too little raw material will slow down production—but too much ties up capital. Stocks deteriorate and store rentals rocket. With all these factors, costs are sub-

ject to long and short term variations; the computer can help to find the right balance, introducing a new level of scientific measurement.

Another application of computers of growing importance in the engineering industries lies in the speeding-up and improvement of machine tool operations. Instructions can be prepared

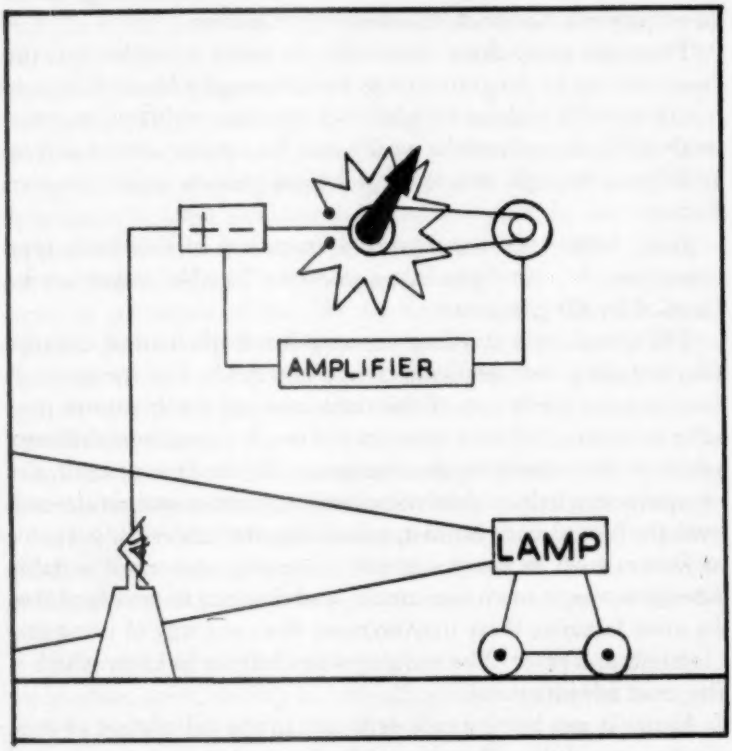


FIG. 3

directly from a drawing and punched on to tape—a comparatively small computer can, from this tape, calculate the motions which the tool must make to machine the part, and can record them in coded form on to magnetic film.

When this film is played back, just as in a tape recorder, the table carrying the work can be made to execute the necessary motions to make the required part and so in a fraction of the time

taken by a human operator make it automatically to an accuracy much better than that possible with a skilled machinist. One of the great advantages of such computerised machine tools is that a wide variety of components can be made without lengthy setting-up operations.

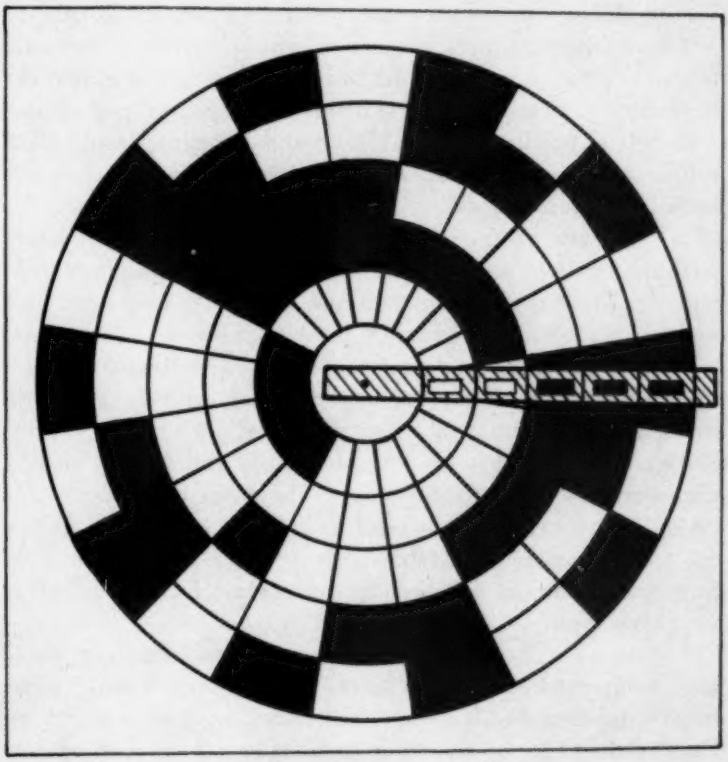


FIG. 4

Now in all these examples information has been fed into the machine by human beings—numbers, and instructions what to do with the numbers. But this is not essential—the information can be derived directly from instruments which detect and measure the state of the outside world. Let me show you how this can be done.

On the right of the picture in Fig. 3 there is a lamp; on the left

a light detector or electric eye which measures the light intensity on its surface; if the light intensity varies it is indicated by a large pointer. If a special metal contact plate (Fig. 4) is coupled up to this pointer, its position can be converted into a number in binary form. As the plate moves behind five fixed electrical contacts different combinations of switches are closed, thus converting the position of the pointer into machine code language.

I have taken the measurement of light because it is very easy to demonstrate but one could measure temperature in just the same way, or pressure, or in fact almost any property of a body.

A new technique which can help and sometimes replace the human observer is 'electronics'. Electronic devices can simulate some of the human senses and can convert all kinds of properties of a body such as, for example, temperature, weight, moisture content or colour, into electrical signals; they can observe events with far greater precision than the human senses—they can provide a record of what they have seen—and, unlike man, "They never get sleepy no matter how late they may have been up the night before". In consequence they can relieve man of much of the monotony of observing events.

This ability to convert instantaneously the reading of any measuring instrument into computer language provides the engineer with a new and powerful tool. Instead of having to rely on information collected laboriously by hand, instantaneous information from any number of instruments can be collected at very high speed.

For instance, I could have four instruments measuring pressure, temperature, flow and level (Plate II)—each instrument turns a digitizer disc like the one already described (see Fig. 4). Each reading may be changing continually—the indications are converted into binary code; the instantaneous position of all the switches is noted by a big rotating switch which, for demonstration purposes, is scanning the four instruments every two seconds, but it could be doing it every thousandth of a second. Each time the rotating switch goes round once, signals from all four instruments are sent as a train of impulses, either directly to a computer or to an electric typewriter. If a model typewriter is switched on and connected for one revolution of the pointer, the information at that instant from all four points is typed out.

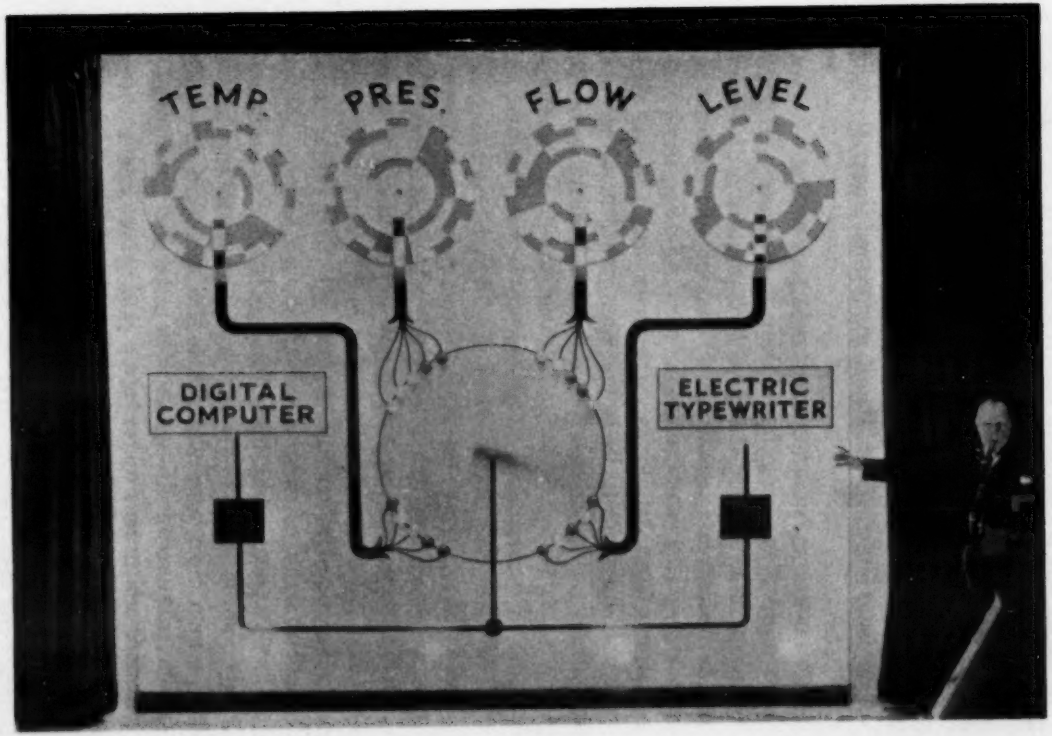

TEMP.
PRES.
FLOW
LEVEL
DIGITAL COMPUTER
ELECTRIC TYPEWRITER

PLATE II

At any time later, if the switch is again closed, the readings at that instant are typed out. This can be repeated as many times as we like.

With this kind of equipment, dial instruments and human recording are no longer necessary; all information is typed out automatically on one sheet of paper. One operator can see what is happening at all points in a plant at any instant. This, in itself, is a great advance both in speed and accuracy, but more important still, it leads directly to full automation, because it is now possible to attach electronic computers directly to electronic sensing elements.

Now although we have seen that a computer is an assemblage of a very large number of quite simple devices, if the instructions given to it are prepared by clever people, quite unskilled people can use it to do very clever things. For instance it can translate from one language to another: it can play games with a human being: it can learn by its own mistakes and remember what it has done. Most important of all, it can make decisions by following alternative courses of action depending on the results obtained in a previous calculation.

The possibilities now opened up by such devices for helping man to gain mastery of his environment are quite startling. We have already seen how a computer can give rapid decisions based on information fed into it either by human beings or by sensing elements. It is but a small step to incorporate executive action, whereby the computer not only makes decisions but takes the necessary action itself. This step, known as "self-optimising" or "adaptive" control has already been taken in a few industrial plants and has already led to greater yields and greater profitability.

We can now forecast the likely pattern of future developments. Firstly, such machines will slowly take over from man all the tedious thinking which has to be done—all the counting, checking, sorting and so on. It is quite certain that in less than fifty years such repetitive work will be as unthinkable as the carrying of burdens on the backs of slaves.

Secondly, such machines will be used to get the greatest efficiency out of existing means of production—less raw material will be wasted, better quality will be achieved, and costs will be reduced.

Thirdly, let us forecast the likely pattern of future development in industrial production—the foundations are already laid, the automatic factory is in sight—a factory where tedious human effort has been eliminated, where efficiency has been increased, where man is the master and not the slave of the machine.

The first step in any transaction is for each customer to enquire the price and delivery of the goods he wants. The computer first examines the current production position, the stocks of finished goods and the stocks of raw materials; it then provides a quotation and a delivery date. If the customer accepts the quotation, the computer then fits the order into the production plan and selects the best raw materials to execute the order at minimum cost; the raw material store is advised of requirements, orders are automatically issued on the suppliers, and the stock is replenished. Production now starts; each production unit in the plant and each inspection device is set automatically by the computer, raw materials are released, and the plant operates to make the required goods; the inspection devices maintain correct adjustment of each machine and report continually on progress —if the product quality falls off, a signal is given that adjustment of a machine is necessary; should breakdown occur a signal is given to the maintenance staff.

When production is completed the new stock position is reviewed, instructions are issued to deliver the goods to the customer, and the customer is charged. Finally, on payment, the transaction is recorded and a receipt prepared.

General directives will always be given by management—introduced into the computer as permanent instructions—but the routine day-to-day business, the routine decisions, the issuing of instructions, the setting-up of the machines, will be undertaken without human intervention.

The similarity between such an automatic factory and the human organism is obvious. In the human body there are senses sending signals to the brain which co-ordinates them and issues instructions to the various muscles; in the factory of the future there will be electronic sensing elements sending signals to a computer which will co-ordinate them and issue instructions to the various machines.

It is a far cry from a child's counting frame to the modern

electronic computer capable of performing complex tasks like this. We must ask, therefore, in conclusion, whether such machines can legitimately be called "brains". We naturally resist the suggestion because until quite recently the behaviour of machines has not in any way resembled thinking—but there are degrees of thinking—for instance we take it as quite reasonable for a machine to multiply two large numbers, but children when they do the same thing in their heads would most certainly call it "thinking".

After all, the first essential of an electronic computer is a very large memory and the first essential of a human brain is also a very large memory; it is estimated, in fact, that the number of nerve cells in a human brain is a million times the number of stars visible to the naked eye—quite a lot—yet this storage capacity is equivalent to about a million feet of magnetic tape which is not an impossibly large store for a computer.

The second essential of a human brain is its ability to retrieve any desired information in a few seconds—the machine can do the same thing but at present very much slower.

The third essential of a brain is the ability to make logical decisions; it has long been known that the nervous systems of animals have these capabilities and that in man the nerve cells function in much the same way as the 'Yes/No' behaviour of the electronic circuits in a computer.

To sum up, there is no doubt that a close similarity exists and that as machines get more complex the similarity will become closer. Just as there are degrees of complexity in computers, so are there in human brains. Quite a small electronic computer can perform many tasks far quicker than a human brain. But no one would suggest that a computer could, or is likely in the foreseeable future to be able to, simulate the brain of a poet like Shakespeare, a painter like Rembrandt, a musician like Bach, or a scientist like Michael Faraday.

EXHIBITS IN THE LIBRARY

1. Optimising equipment in control of three lamps, to produce given illumination at minimum cost. Individual lamp efficiencies were manually pre-set. Current consumed was measured digitally by a Giannini shaft encoder attached to a Bristol recorder. The optimiser continually adjusted the brightness of pairs of lamps, while keeping total illumination constant. Those adjustments which decreased the current taken were repeated until the minimum was reached.

Logical elements used were half-cycle magnetic amplifiers and diode gates,

working at 400 c/s. The lamps were controlled by motor-driven auto-transformers. The M-type motors were driven directly by logic units.

2. A complete eletronic computer installation consisting of a National-Elliott 802 computer and Creed Page Printer. The solid state computer, housed in a desk size cabinet, was shown in action. The program demonstrated was the printing of schedules of the capital and interest content in each instalment of loans of varying amount repaid at different interest rates over different periods.

3. Two manual key-operated tape-punching machines. The operators demonstrated the preparation of data for the calculation of a payroll on an electronic computer.

4. Board chart illustrating the flow of information and the processes in a computing application.

All the exhibits were arranged and operated by *Elliott Brothers (London) Ltd.*, a Member of the Elliott-Automation Group.

THE MENACE OF VIBRATION IN ENGINEERING

By R. E. D. BISHOP, M.A., M.S., Ph.D., D.Sc.(Eng.)
Kennedy Professor of Mechanical Engineering in the University of London

Weekly Evening Meeting, Friday 11th December, 1959

A. G. Gaydon, D.Sc., F.R.S.
Vice-President, in the Chair

THOMAS YOUNG, who published his lectures to the Royal Institution, complained in them that the subject of vibration and sound was

> ". . . treated in a very abstruse and confused manner, or connected entirely with the practice of music, and habitually associated with ideas of mere amusement."

Of course he was perfectly right to demand that the subject be taken seriously. Atoms vibrate, the transmission of sound and light waves entails vibration. Our hearts beat and our lungs oscillate. In short, vibration cannot be disregarded by a scientist. This discourse is specifically concerned, however, with vibration as something which engineers have to prevent, or at least control.

Why should it be desirable to prevent vibration? The most obvious reason is the acute suffering that it can cause, as anyone who is seasick will affirm. Another reason for suppressing vibration is that it may cause malfunctioning of instruments (by the blurring of optical images for instance) or it may affect the performance of radio valves. But the most insidious thing about vibration is that it can cause breakage by fatigue of metal parts with little or no warning—as with the Comet disasters.

Low frequency shaking

Of the various forms of vibration one is particularly suitable as an introduction to this subject. For want of a better word, let us call it "shaking". It is the sort of slow oscillation that is performed by a small boat at sea. The boat doesn't creak much, so that it performs its motion bodily without distortion.

Now consider a short shaft. It is not possible to make it—or anything else for that matter—with complete precision, so that its centre of mass will not lie exactly on its axis. If the shaft is

mounted so that, like the boat, it can shake without distortion, then it will shake when it is rotated.

If the shaft were restrained and an attempt were made to hold its bearings still, then a fluctuating force would be necessary to achieve this. To obviate the need for a fluctuating force, the rotor must be balanced in a balancing machine. The magnitude of the unbalanced force increases as the square of the speed, so that high-speed rotors (such as those in gyroscopes) demand very careful balancing.

One of the first causes of vibration in machinery was the construction of unbalanced reciprocating machines. An early steam engine could have a piston and piston rod weighing as much as half a ton and when these were accelerated to and fro along the cylinder axis they produced a mighty heaving. So long as the operating speeds of these engines were kept very low the vibration could be kept at an acceptable level; but speeds could not be kept so low so that the inertia forces developed in such machines became a major nuisance. It became necessary to practise balancing.

Free vibration

The source of "shaking" motions is sometimes easy to find and, often, judicious balancing is all that is needed for its suppression. The structure which does the vibrating experiences a pulsating force; in the rotor it is an inertia force caused by rotation while in the old steam engine it was caused by reciprocating parts. And in the small boat it is a varying buoyancy force.

Unfortunately mechanical vibration is a much more complicated phenomenon than this, and it is necessary now to examine why this is so. Pretty well every object possesses the ability to vibrate freely on its own when it is disturbed. Now free mechanical vibration as such is not often of much interest in engineering; but it is essential to have some understanding of its nature.

We normally identify free vibrations with some characteristic frequency of oscillation. When A above middle C on the piano is struck, a note is heard which has a characteristic frequency of 440 vibrations per second. In fact these frequencies are *dominant* frequencies. Any body can vibrate freely at one or more of a number of characteristic frequencies. The piano strings do not

vibrate only at 440 vibrations per second, but also exhibit small overtones with 2, 3, 4, . . . times 440 vibrations per second. It is from the overtones that we know it is a piano and not a flute or a bassoon that is being played.

The essential feature of all these characteristic frequencies for any given body is that each one of them is associated with a different *shape* of vibration. To return to the piano string, 440 vibrations per second corresponds to a single loop and there will be a smaller vibration at 880 vibrations per second with a different

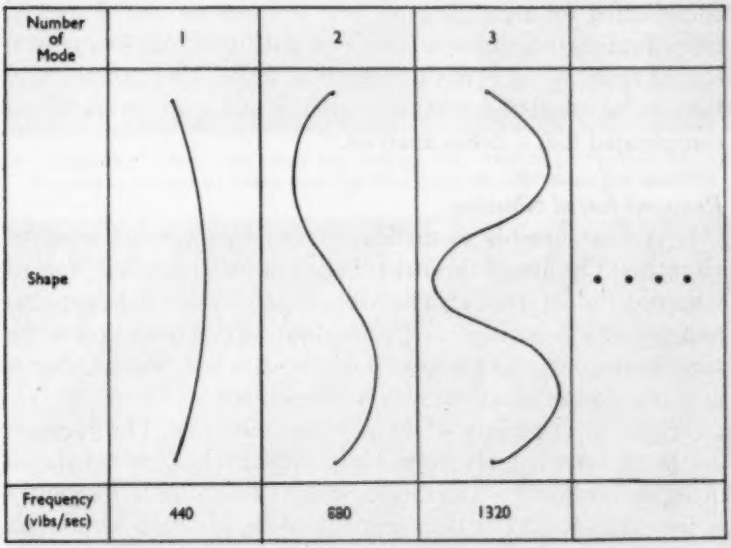


FIG. 1. The shapes associated with the vibrations of a piano string.

shape (two loops) and so on. This is illustrated in Fig. 1.

There is one other feature of free vibration which must be mentioned, namely that of damping. A bell goes on ringing for a very long time after it has been struck because of the absence of large friction forces within and around the bell to dissipate its energy in the form of heat. On the other hand, if a car is bounced up and down on its springs and is then allowed to oscillate on its own the movement dies away quickly because of the construction of the suspension springs and the friction forces which arise in them and in the shock absorbers. As a general rule we should

expect more violent oscillations in structures which, like the bell, have little damping than we should in structures whose rate of energy dissipation is high.

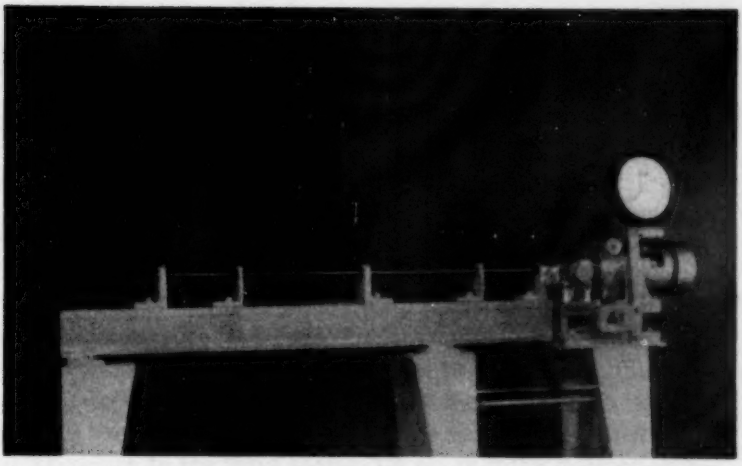
So far as we are concerned here, it is merely necessary to know that bodies and systems can vibrate freely in a large number of forms, each being associated with its own characteristic frequency (measured in vibrations per second). It is as though these systems would like to oscillate in these shapes, and at these frequencies, and will do so if given a little encouragement. But mechanical structures are not like the taut string in that they are usually too complicated for their characteristic frequencies and shapes of free vibration to be known. Neither are their natural frequencies spaced apart so nicely in the numerical sense. These things may have to be calculated, but the damping is almost invariably so complicated that it defies analysis.

Resonant forced vibration

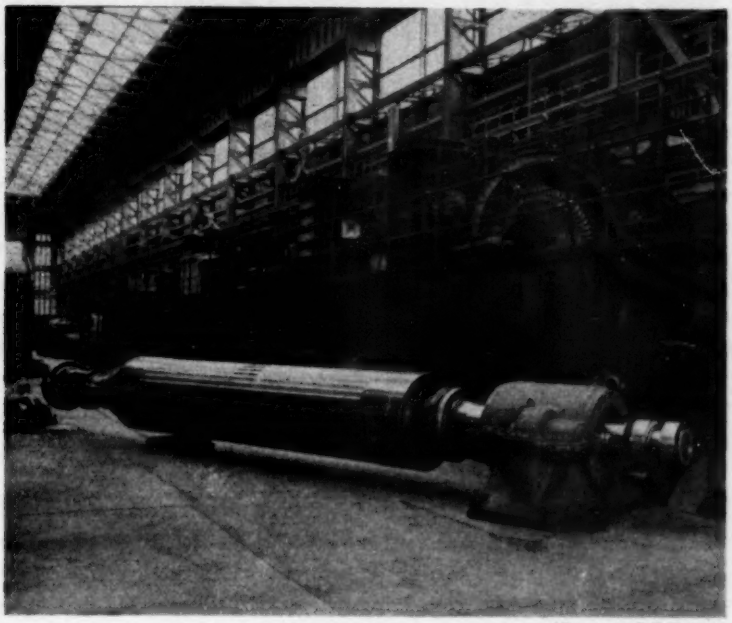
It is now possible to distinguish between various types of vibration. The first of these that I shall mention is called "forced vibration" and it is set up in the vibrating structure by the application to it of a pulsating force. The vibration that is set up has the same frequency as the forces which cause it and, indeed, that is how this type of vibration may be recognized.

"Shaking" is, strictly, a form of forced vibration. The fluctuating inertia force in early steam engines and the force of unbalance in the short rotor cause vibrations which have the same frequency as the excitation. Why then should shaking be mentioned on its own? The point is that the force which causes a shaking, causes an intolerable motion when its frequency of application is below the frequency with which the vibrating structure could oscillate freely on its own.

This may be illustrated with a simple example. The long thin rotor shown in Plate IA will vibrate freely sideways like a piano wire at a far lower frequency than the short dumpy rotor. It too is unbalanced so that when it is run up to speed it will tend to wobble as the other did. But now the vibration caused by unbalance can approach and pass the first natural frequency. When the rotation speed, and thus the frequency of the inertia force is in near coincidence with a natural frequency—in this case the



A. A thin shaft which can rotate fast enough for its speed (in revolutions per second) to exceed its lowest natural frequency (in vibrations per second).



(Courtesy *G.E.C. Ltd.*)

B. A turbo-alternator rotor.

PLATE I

lowest—a state of resonance is set up. That is to say, the system is stimulated at a frequency with which it would *like* to vibrate freely. The shaft responds eagerly to this form of coaxing so that, at resonance, it whips violently exhibiting a phenomenon known as "whirling". It behaves like this when the rotation speed coincides with *any* natural frequency.

The conventional turbo-alternator, which generates electricity, is a monster whose rotor can weigh anything up to 100 tons. To maintain a 50 c/s supply, the turbine has to drive a rotor like that shown in Plate Ib at 3,000 r.p.m. The accurate calculation of the dangerous speeds of these things is not easy and yet they must run through them. If this rotor were to get into a sufficiently violent wobble, it would burst and cause hundreds of thousands of pounds worth of damage, and doubtless account for human lives.

To return to the main theme, we see that the distinction between the forced vibration of shaking, as it is described earlier, and forced vibration as it relates to resonance is a matter simply of the relation between the exciting frequency and the lowest natural frequency.

The structure shown in Plate II is a simple arrangement of metal strips brazed to each other to form a sort of building frame. The little electric motor drives a wheel bearing an unbalanced mass. If the speed of the motor is gradually increased it passes through the shaking range at a fairly low speed and then proceeds to build up resonance in the first, second, third, fourth . . . resonant shapes. It is perhaps worth noting that this structure is a trivially simple one by engineering standards. Even so, the calculation of (say) the lowest half dozen of its natural frequencies and shapes of free vibration would be a major undertaking even if a digital computer were available; it would be a tremendous task without one.

Consider now a completely different source of excitation. A Pelton Wheel is somewhat like a very well-constructed and designed water wheel. The wheel carries buckets attached to its rim and a tangential jet of water, usually of very high speed, plays onto the buckets and drives them round. Any one bucket thus receives a periodic blow. Now each bucket has its own range of natural frequencies and if one of them were to concide with the frequency of impingement of the jet then the bucket would

vibrate while it went round, and it might possibly break. This has, in fact, happened once or twice.

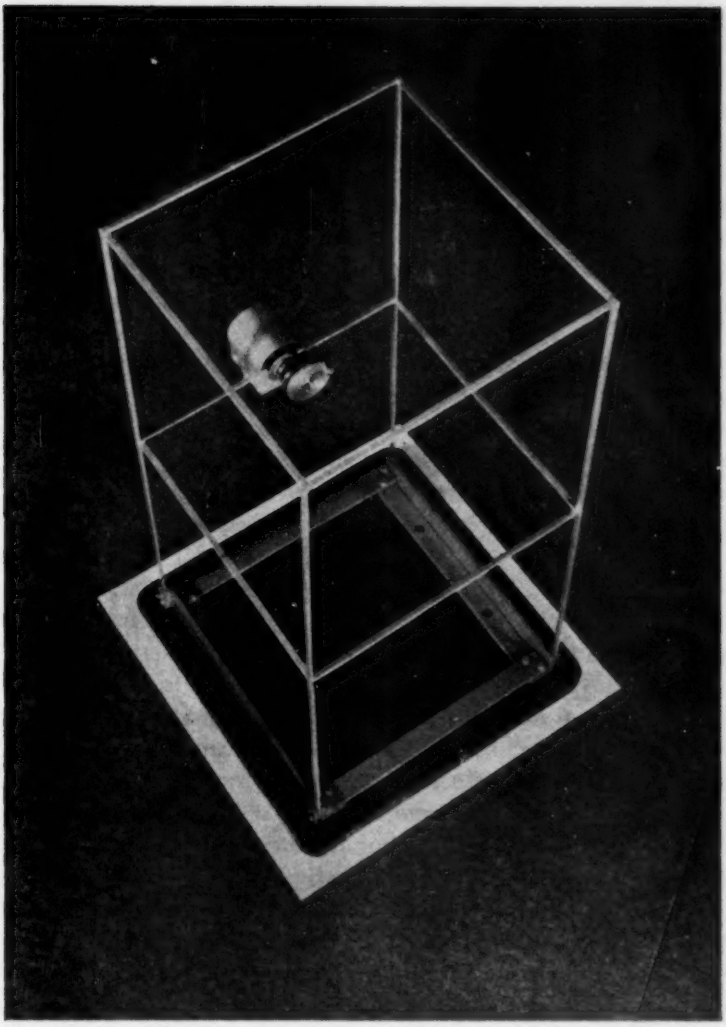
There are three points here worth noting. First of all the speed of the wheel has to be kept constant since it drives an alternator whose speed must be constant for electrical reasons. Thus if coincidence does occur it will be maintained. Secondly, each bucket is supposedly identical with all the others so that the system has a number of natural frequencies which will be almost (but, due to unavoidable imperfections, not quite) equal. This raises certain difficulties in vibration analysis both on the side of theory and of measurement. The third thing is that each bucket is attached to the main wheel and its frequencies and modes are partially determined by this attachment. Now this has a bearing on one branch of vibration analysis which needs further research, namely the effects on the vibration characteristics of a large body of small bodies attached to it.

Sometimes some small object in a motor car will oscillate violently when a slight vibration from the engine permeates the whole vehicle. This may occur, for instance, with the rear view mirror. The mirror is unlikely to affect the dynamics of the whole vehicle appreciably since it is so small, and analysis of the motion is quite straight-forward; we can assume that the mirror does not affect the vibration of the car at all. Equally, the vibration of some larger component can be dealt with by fairly standard methods. Thus we can calculate the effects of something like the back axle on the shapes, (or "modes") and frequencies of free vibration. But violent local oscillation of an object whose effect is somewhere between that of the small mirror and the large back axle can sometimes be difficult to analyse.

There are many sources of excitation which will produce a forced vibration. For instance the shaking near the stern of a ship is caused by hydrodynamic forces; these are generated as the propeller blades pass the nearest point of the hull. Again, it is for fear of resonance that soldiers "break step" and do not march across bridges.

Random vibration

Forced vibration as a phenomenon has been familiar to engineers for many years. Let us turn now to a rather special form



A model frame carrying a vibration exciter whose frequency can be varied.

PLATE II

of it—"random vibration"—which is beginning to attract a great deal of attention, and which demands a completely different analytical approach.

The turbulent flow in the jet issuing from a gas turbine engine sometimes causes panels to vibrate in aircraft structures. The frequency and intensity of the excitation is, to say the least, ill-defined. In fact, one may assume that there is a complete mixture of frequencies. The problem is therefore studied as one of statistics. The necessity for this can be seen by comparing strain-gauge signals taken from (i) an ordinary resonant structure and (ii) from the wall of (say) a wind tunnel.

Although turbulence is a common source of random vibration, it is far from being the only one. For instance a wheel which runs along a rail is subject to it, simply because neither the wheel nor the rail can have perfectly true surfaces. Again, those who have to rely on smoothness of running find that ball and roller bearings are not the blameless components that they appear to be, for the same reason.

Self excitation

Another type of vibration is known as "self excitation". This is not caused by a fluctuating force, but it does demand the existence of some steady source of energy. The vibration is, so to speak, caused by itself (in that the natural movements extract energy from the steady source) and takes place at one or other of the frequencies with which free vibration could occur. This phenomenon is exhibited very clearly and uncomfortably by my bicycle when the front brake is applied. Frequency is the clue to whether a vibration is a forced one or is due to self excitation.

The very generality of the requirement that only a source of energy is needed makes this form of oscillation most important and often most perplexing. The explanation of the bicycle shudder is to be found only from a detailed analysis of the surface physics of the brake block and the rim.

Those who live in the southern region and travel in trains down through New Cross will know what violently rocking trains are like. In an electric train the necessary input power comes from the motors and the build-up of the motion is something which has puzzled railway engineers for many years. In fact this

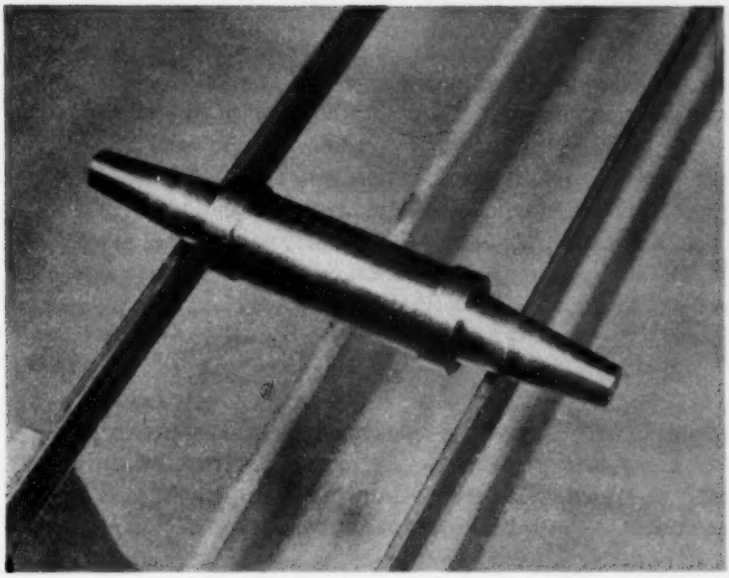
problem is so perplexing that an international competition was held recently in an effort to find a solution. It failed. An oscillating railway coach is, from the vibration analyst's point of view, a perfect nightmare; it is a mass of unknown stiffnesses, clearances and frictions and the physics of the source of the self excitation has never been satisfactorily explained.

Even the simplest possible vehicle can be made to oscillate simply by rolling along a rail. The roller shown in Plate IIIA has coned running surfaces as every railway train wheel must to preserve the centring action. When it runs slowly down the inclined rails it behaves as a civilized roller should; if put on straight it runs straight, and if put on cocked it will simply zig-zag down the track. But if the speed is increased—here, by raising one end of the track—the zig-zag motion builds up. In this simple example the effect is produced by the complicated system of strains at the points of contact of the cones and the track and even this is a matter which is not adequately sorted out yet.

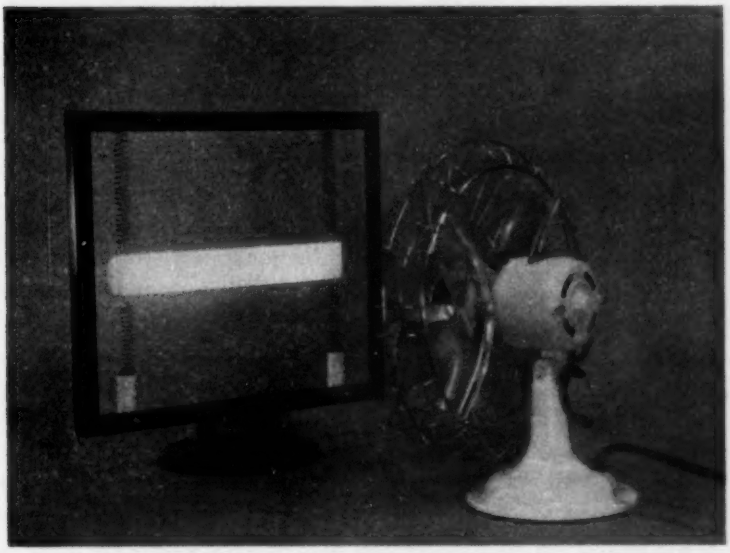
This problem of railway trains is at present one of real importance and some experiments which are being made by British Railways at the moment may finally put us on the path towards a solution.

A rotating shaft of one form or another was used to illustrate shaking and resonant forced vibration. The slender rotating shaft (Plate IA) can be used to demonstrate self excitation too. It will be remembered that, when run up to speed, the thin shaft ran through critical speeds at the lowest natural frequencies of the shaft in the absence of its rotation. If the previous steel shaft is replaced by a wooden one the behaviour is changed. The first critical speed is approached, as with the steel. But now it is not possible to quell the vibration again by increasing the speed; the vibration just goes on and, no matter what the rotational speed, the shape (and in fact the frequency too) corresponds with the first natural frequency.

Now this is quite easily explainable in terms of the extra friction that goes round with the shaft; the fibres of wood rubbing against each other set up much greater friction forces than do the elements of steel. Just why this comes about need not concern us here, but let us reconsider the large alternator rotor of Plate IB; here we have a steel forging with strips of copper embedded in it



A. A simple coned roller whose yawing oscillations will increase if its rolling speed is high enough.



B. A spring-suspended bar of semi-circular cross-section placed in a flow of air. The flat side of the bar is presented to the fan.

PLATE III

and rubbing against it as it bends through rotation. If one of these monsters were to behave like the wooden shaft, as a result of this, the results would undoubtedly be tragic because fatigue of the rotor would then be a possibility.

There are many ways in which self excitation can arise. One particularly troublesome example is to be found in the chattering of machine tools (which causes a rippling of the surface of a piece of metal as it is turned or milled). Again the oscillation of castored wheels (as in some tea trolleys) has led to some disastrous aircraft accidents.

Self excitation from fluid flow

Many examples of self excitation arise from the flow of fluids, the necessary energy input to the vibrating system being extracted from the stream. Consider the system shown in Plate IIIB, for instance. The fan blows its current of air past a wooden bar which is mounted on springs. So far as the bar is concerned then there is an energy supply to it in virtue of the motion of the air. The bar bounces up and down perpendicular to the air stream. But there is no fluctuating applied force, as such.

The explanation of this motion demands a detailed study of the flow of the air round the wooden bar and here it will be noted that the bar has a semi-circular cross-section. While a detailed discussion of the fluid mechanics of this motion is not necessary here, it will be seen that one might be needed if the phenomenon were being met for the first time and had to be suppressed. It will also be seen that a bar suspended in this way has several shapes of low-frequency vibration, only one of which is the up and down motion which actually takes place. The bar could oscillate backwards and forwards in the direction of the air stream or it could rotate about its middle point so that one end goes up while the other end goes down. Thus an investigation into the likelihood of vibration to build up would have to be such that the system is allowed to select whichever of its own vibration shapes it chooses to move in; and in engineering those shapes are not normally known in the first place.

The apparatus of Plate IIIB helps to explain the oscillation of electric transmission lines under certain weather conditions. When the lines have a coating of ice, they no longer have a circular

cross-section. The wind may then cause them to build up a slow vibration, sometimes with an enormous amplitude.

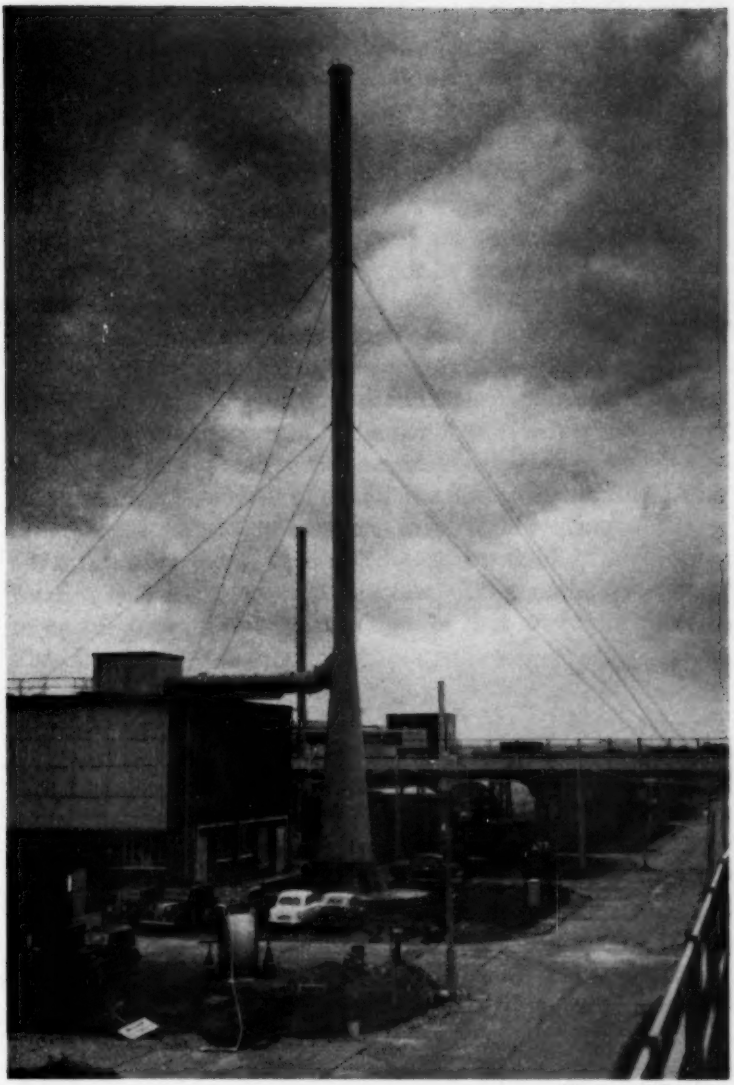
An aeroplane is subjected to a rush of wind too so that it also may vibrate. The phenomenon is known as flutter and the study of it has been a matter of fundamental importance in aeronautical engineering since the First World War when it was first recognised. It is not proposed to go into the details of this form of analysis here, although it has grown up into a science of its own with the name of Aeroelasticity.

Plate IV shows a very tall steel chimney which has, in fact, no firebrick lining. Steel chimneys of this sort are much less expensive than brick structures and have other attractive features from an owner's point of view. When this particular chimney had been erected it was found to sway in winds of a certain strength. This was caused by the periodic shedding of vortices in the wind, first from one side and then the other; these caused pressure fluctuations on the sides and hence the swaying, and once the swaying had started it was self-maintaining. Here is another problem of self excitation caused by air flow. Again the explanation lies in an understanding of the physics of the problem and it might be added that the physics of this particular problem is still insufficiently understood for engineers to produce a reliable building code to prevent this sort of motion. The way to stop a chimney like this from swaying is simply to guy it and preferably to put friction devices in the guys.

It is a main feature of self excitation that the oscillation nearly always occurs at a natural frequency of the system concerned and can often be recognised from this. The cure for self excitation is often to add friction to the system (as with the chimney by putting it into the guy lines or, alternatively, putting in the firebrick lining).

Aeroelasticity and flutter have already been mentioned. It is necessary to go back now to point out that, with flutter, it is necessary to make allowance for modification of the inherent natural frequencies of aircraft. Moreover the shape of an aeroplane is such that it is not possible to put the friction in where it is wanted. It is for these and other reasons that aeroelasticity has become a specialised subject in its own right.

Some idea of the diversity of the forms which self excitation



(Courtesy *U.K.A.E.A.*)

An unlined steel chimney which (before the attachment of guys) swayed in winds of a particular speed.

PLATE IV

can take may be had from the coffee pot shown in Plate V. It lives in University College Hospital Medical School where it habitually rocks back and forth on its slightly rounded bottom, while it is kept warm on a hot plate; this is due to an inflow of energy, not from a fluid motion, but in the form of heat. Here again an explanation of the phenomenon demands a detailed understanding of what goes on (and it might be added that, in this case the liquid in the pot need not be boiling and can, in fact, be almost cold). This may not be at all easy in practical problems.

The number of examples which can be used to illustrate self excitation is almost limitless. One more must suffice, namely that of oil whirl. One of the major outstanding problems of mechanical engineering at the moment is the fact that a shaft which runs at high speed in a plain journal bearing may whip to and fro on account of the behaviour of the oil film upon which it rides. Very often there is no real alternative to using plain bearings and their advantages are many. It is not difficult to think of high-speed rotating shafts which would be a first class menace if they were to be subjected to oil whirl. Think of that alternator rotor in Plate Ib.

Other types of vibration

There is another form of vibration known as 'non-linear' vibration. It derives its name from the fact that the mathematical equations which govern it do not conform to the usual pattern; they are usually very difficult to handle mathematically. This type of motion is often observable in vibrations of large magnitude. Thus a self excited oscillation, such as occurs in my bicycle or in a swaying railway train grows as a result of self excitation and is finally limited by the interference of effects which are not covered by the simple theory which may be available to predict that growth.

Not very much can be said about this aspect of vibration in a general discussion such as this, since it is difficult to point out its characteristic features. A non-linear system can have all sorts of queer habits. Thus a given fluctuating stimulus can sometimes produce a motion having one of two alternative intensities, the intensity which actually prevails being dependent upon the pre-

vious history of the excitation. Let us merely note, then, that non-linear oscillation is often the observable end-product of self excitation or of violent resonant forced vibration.

It is by no means uncommon for a system to be subjected to two vibrations at the same time. This may give rise to the familiar phenomenon of "beating", by which the intensity of the motion slowly fluctuates between violent—and very small vibration. This super-position of vibrations is often such that the frequency of one component is some fixed multiple of the frequency of the other; this state of affairs raises several interesting points and, occasionally, a good deal of practical difficulty.

Yet another type of vibration is performed by a system while it suffers a disturbance of limited duration, as in an earthquake or during the process of impact. The disturbance produces a "transient" motion which may, or may not, involve breakage. Investigations into this type of vibration often lead to consideration of stress waves within the systems concerned (like those which are propagated through the earth during earthquakes); for the question of whether a motion shall be treated as a wave propagation or as a large number of superimposed vibrations is entirely one of convenience. But this merely leads us to another enormous field of research.

Conclusion

Vibration is such a menace that many engineers are engaged on research in the subject. In this discourse it has not been possible to indicate, even in general terms, all their lines of investigation. We need data—even of the crudest kind—on the vibration which atomic weapons will impart to surface and underground structures. Again the need of a solution to the oil whirl problem is urgent—even the vibration of a simple rotating shaft is imperfectly understood. We cannot yet explain the swaying of railway trains.

We can, however, predict and avoid many types of vibration. Engine components, aircraft structures, bridges, and so on, are not the unpredictable systems they were in this respect. And modern electronic and computer techniques have speeded up this advance.

A great deal could be said about the theoretical side of vibra-

Courtesy *U.C.H.M.S.*

A self-excited coffee pot

PLATE V

tion, but a single remark must suffice here. It is that vibration is a subject which has led to renewed interest in a particular branch of pure mathematics, namely matrix algebra. As a result matrix theory has been greatly developed in the last twenty years; in fact one of the best known standard works on matrix theory was written (at the behest of the Aeronautical Research Council) by three men whose interests lay primarily in the flutter of aeroplanes.

During the course of the lecture, two extracts from films were shown. The first showed an artifically-induced vibration of the tail-unit of a Lancaster bomber in flight. The lecturer is indebted to the Chief Scientist of the Ministry of Aviation for the loan of the film. The second showed the violent oscillation which led to the destruction of a great suspension bridge over the Tacoma Narrows in Washington State. The bridge collapsed after it had been in service only a few months. The motion was started (as one of self excitation) by a steady wind of about 40 m.p.h. and it became violently non-linear. The lecturer is indebted to the Institution of Civil Engineers for the loan of this film.

EXHIBITS IN THE LIBRARY

Demonstrations showing (a) the forced vibration of a steel plate and (b) the excitation of a beam (arranged by *Research and Control Instruments Ltd.*); (c) the vibration of a turbine blade and (d) the use of vibration in grain conveyors (arranged by *G.E.C., Ltd.*); (e) the non-linear oscillation of a rolling coned rotor, (f) the 'flutter' of aircraft and (g) the 'shimmy' of castors. There were also exhibits of anti-vibration mountings, vibration measuring instruments and metal parts which had been subjected to 'chatter' (arranged by *Prof. R. E. D. Bishop and the Department of Mechanical Engineering, University College, London*).

FUEL CELLS: WILL THEY SOON BECOME A MAJOR SOURCE OF ELECTRICAL ENERGY?

By F. T. BACON, M.A.
Consultant to the National Research Development Corporation on Fuel Cells

Weekly Evening Meeting, Friday 12th February, 1960

H. D. Anthony, M.A., B.Sc., Ph.D.
Vice-President, in the Chair

THE efficiency of all heat engines, that is to say, engines in which heat is converted into mechanical work, is governed by Carnot's cycle; this means that the efficiency is limited in practice by the difference in the temperature at which the heat is taken in by the working fluid and the temperature at which it is rejected. It is the possibility of avoiding the Carnot limitation which constitutes the main, but not the only, reason for interest in fuel cells.

A fuel cell can be defined as an electrochemical cell in which the free energy of combustion of a fuel is converted directly into electrical energy. The first fuel cell that was made to work at all was the Grove Gas Battery; this was in 1839. Grove used platinized platinum electrodes sealed into the tops of inverted test tubes, and dipping into a dilute solution of sulphuric acid; hydrogen was contained in one of the test tubes and oxygen in the other. The principle of operation of the hydrogen/oxygen cell is simply a reversal of the process of the electrolysis of water.

A big step forward was made in 1889 when that wonderful chemist Ludwig Mond, in conjunction with Charles Langer, started some experiments with the object of improving the Grove Gas Battery, again using hydrogen and oxygen. He came to the conclusion that two fundamental principles must be observed; first, the current density must be kept very small; and secondly the electrodes must be kept substantially dry, though of course they must be wetted by the electrolyte on one side. The electrodes consisted of very thin sheets of platinum, perforated with a very large number of holes; the electrodes were coated with finely divided platinum, or what is known as platinum black, thus giving the very large surface that he wanted; the electrolyte of

dilute sulphuric acid was entirely contained in the porous diaphragm of asbestos board or other materials, thus keeping the electrodes more or less dry.

PRESENT DAY FUEL CELLS

There are various ways of classifying the different types of fuel cell that are now being tried, but it is convenient to divide them up into those working at atmospheric temperature up to say 100°C; those working at a medium temperature, around 200°C; and those working at a high temperature, say 550°C, and upwards, with electrolytes of fused salts.

National Carbon Cell

The most outstanding low temperature cell is undoubtedly the one developed by Kordesch of the National Carbon Company in the United States. He usually makes use of concentric tubular electrodes of porous carbon; though thin flat plates have been used as well. The electrodes are waterproofed, using a kind of paraffin wax, and this prevents the small pores from being flooded with liquid. An alkaline electrolyte of strong potassium hydroxide is employed, a temperature of about 65°C and usually atmospheric pressure, though higher pressures have been tried; hydrogen is the fuel and either oxygen or air can be used as the oxidant; the water formed is carried away in the hydrogen stream, in the form of water vapour. If the current density is increased too much, the hydrogen electrode becomes flooded or drowned with water and the performance falls. The great improvement in the performance of this type of cell has been obtained by very careful activation of the electrodes. A little explanation is perhaps required as to the meaning of the word activation. First, gas electrodes should in general be made with a very large internal surface, like a sponge; and secondly the activity can be further increased by impregnation with catalytically active materials.

Justi Cell

Some other work on low temperature fuel cells is going on in Germany, at the Brunswick Technical High School, using extremely active metal electrodes with a very large surface, and it

has been said that organic liquids, such as certain alcohols can be oxidised electrochemically at quite low temperatures.

Redox Cell

In this type of cell, advantage is taken of the fact that certain metal ions can exist in two different forms in an electrolyte; for example, iron can exist in the form of ferrous or ferric ions; one is in a more oxidised form than the other. So a cell can be constructed with, as it were, two different electrolytes separated by a semi-permeable membrane or diaphragm, which will allow the ions to travel through it but which will not allow the two electrolytes to mix. The electrodes which conduct away the current, are inert electrodes, generally porous carbon; they are kept at different potentials by the two different electrolytes. One electrolyte is kept in an oxidised state by, for example, bubbling air through it in an external vessel; and the other electrolyte is kept in a more reduced state by treating it somehow with the fuel, again in a separate vessel.

Ion Exchange Membrane Cell

The novelty of this cell is that it makes use of an ion exchange membrane as the electrolyte. It is impossible to go into a detailed description of ion exchange membranes, except to say that it has fairly recently been discovered that certain resins are quite good electrolytic conductors. Hydrogen is the usual fuel, and either oxygen or air can be used on the other side; the internal resistance is high, so the performance is rather low. The basic advantages of this cell are that, if the electrolyte is of the acidic type, ordinary untreated air, containing carbon dioxide, can be used without any danger of carbonating the electrolyte; and further, as the current is carried by hydrogen ions, the water is formed at the oxygen electrodes and can be carried away in the form of water vapour by simply blowing air through the cells.

High Temperature Cells

These cells use a fused salt as electrolyte, instead of an ordinary solution of alkali or acid in water. There is some important work now being done in Great Britain on this type of cell at the Sondes Place Research Institute, in the Netherlands at the

T.N.O. laboratories in The Hague, and also in various laboratories in the United States.

Taking a typical high temperature cell, the electrolyte, which consists of a mixture of carbonates is contained in a porous diaphragm of sintered magnesium oxide; this has one great advantage that it prevents the electrodes from becoming flooded with electrolyte; it is silverised on both sides. The electrodes in this

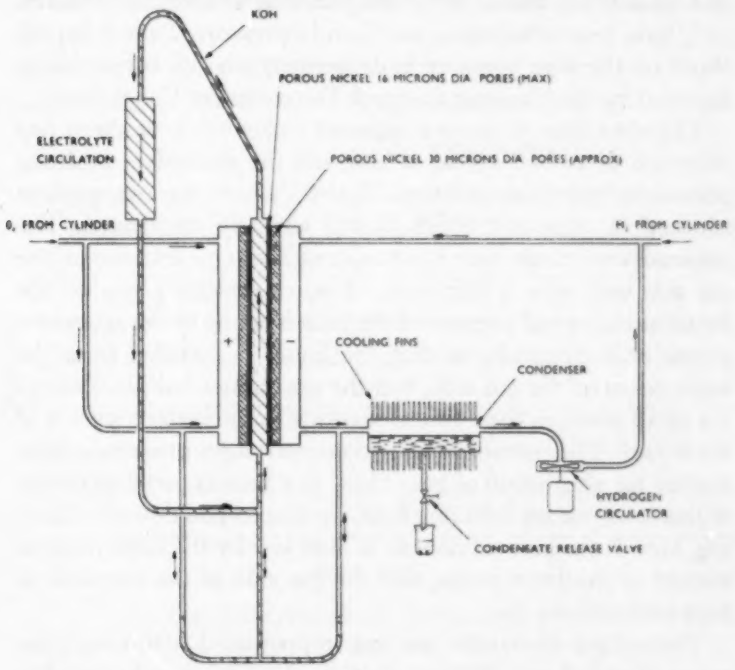


FIG. 1

cell are constructed of silverised zinc oxide. It may operate from say 550°C up to 800°C, but difficulties with corrosion become greater as the temperature is raised; the pressure is atmospheric.

The great advantage with this type of cell is that it will consume impure industrial gases, or vapourized hydrocarbons such as kerosene, and air; this is of course a fundamental advantage in a genuine fuel cell, using cheap and readily available fuels. The chief difficulties are probably associated with temperature strains in the magnesia diaphragm and creepage of the molten

electrolyte, but small single cells have been operated over a period of months without failure; and two cells in series have been tried successfully.

Medium Temperature Cells

The reacting gases in these cells are usually hydrogen and oxygen; the theoretical efficiency at atmospheric temperature and pressure is about 83% and practical efficiencies of about 55% have been obtained at 200°C and a pressure of 400 lb/sq. in. Work on the high pressure hydrogen/oxygen cell is now being financed by the National Research Development Corporation.

The electrodes of porous sintered nickel are now about one sixteenth of an inch thick, or less, and the electrolyte is strong potassium hydroxide solution. Figure 1 shows the arrangement adopted in 1949 and which is still virtually unchanged. The electrodes are made with a pore size of about 30 microns on the gas side and with a thin layer of much smaller pores on the liquid side; a small pressure difference is set up in the apparatus across each electrode, so that the liquid is expelled from the large pores on the gas side, but the gas cannot bubble through the small pores on the liquid side owing to the surface tension of the liquid. The interior of the 30 micron pores presents a large surface for absorption of gas. Thus, in a porous metal electrode of this kind, we are fulfilling both conditions laid down by Ludwig Mond; the current density is kept low by the large internal surface of the large pores, and the gas side of the electrode is kept substantially dry.

The oxygen electrodes are first impregnated with mixed nitrates of nickel and lithium; they are then dried and roasted in air at about 700°C; in this way they are coated with a conducting oxide layer which is very resistant to corrosion in the cell. Oxygen electrodes treated in this way have lasted for 1500 hours in the cell at 200°C. with a drop in output of less than 4 per cent.

The present 10 in. diameter electrodes are not strong enough to be self-supporting against the pressure difference, so they are sintered directly onto solid plates of nickel or nickel-plated steel, which have a large number of holes drilled or punched through them so that gas can readily get through from the other side. Figure 2 shows the best cell characteristic so far obtained with

this size of electrode and it will be seen that currents as large as 320A have been achieved. Longitudinal ports are provided for feeding the two gases and the electrolyte to each individual cell. If bipolar electrodes can be made, a great saving in space and weight will be obtained.

Plate I shows the largest battery built up so far; it has 40 cells, giving an open-circuit voltage of about 40 volts; this gave a performance of 100A. at 32V, or 3.2kW., and 240A. at 24V, 5¾ kW.

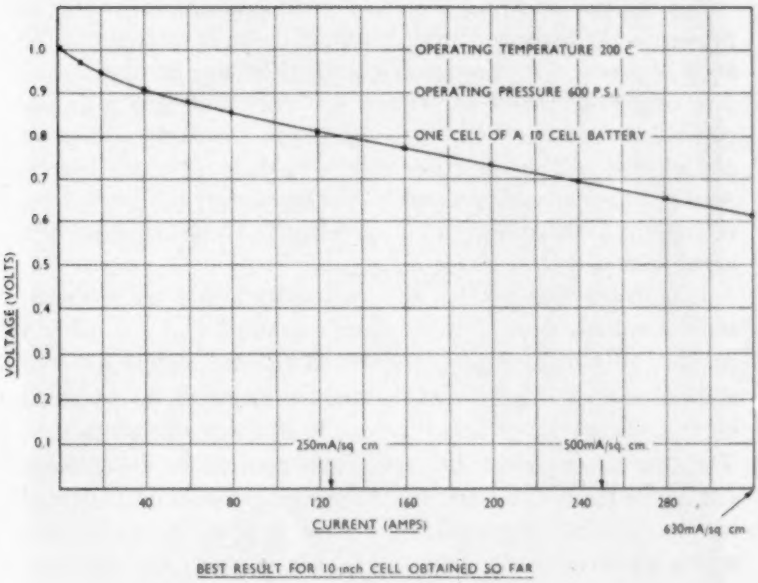


FIG. 2

ADVANTAGES AND DISADVANTAGES

It is quite plain that if a fuel cell can be produced which will accept ordinary fuels such as coal, oil or gas, and atmospheric air, a vast field of application is open to it, both on a large and small scale. Unfortunately, coal must be ruled out, as there is no sign of any cell which can make use of it direct; so we are left with oil in its various forms which can easily be vapourised if necessary, and gas which may be made from coal. Both oil and gas could be considered for large and medium scale generation, especially where natural gas is available; and the piping of

natural gas over really long distances is now being considered. For large scale generation, oxygen would probably be too expensive, so air would have to be used. A pressure cell would seem out of the question, owing to the cost of compression, so it seems fairly certain that a high temperature cell with a fused salt as electrolyte is the answer in this case. Direct current is of course generated, so large scale inversion would have to be considered, unless the device is used for say a locomotive where direct current is desirable.

But the cell on which there is a great deal of controversy at present is the hydrogen/oxygen cell. If it can be brought to the stage of practical application is it going to be any use in practice? The objections raised are mainly that pure hydrogen is an expensive fuel and is difficult to store; and the oxygen must be carried too, and this is more expensive than air which is free. And of course there is no highly developed distribution system, equivalent to that for petrol or diesel fuel. These are important arguments and must be faced.

It is usually agreed that the hydrogen/oxygen cell is essentially a storage device, rather than a genuine fuel cell using a primary fuel, and furthermore, it will be used mainly for road and rail traction. This means that the two gases will be produced by the electrolysis of water, probably in a separate apparatus. Thus the existing electricity grid would provide the distribution system for the fuel, electricity; and the gases would be generated locally. The battery would of course produce direct current which is convenient for driving a vehicle. Considerable developments have taken place in recent years in the field of high pressure electrolysers, and this should have the effect of reducing the cost of production of compressed hydrogen and oxygen in course of time.

Then there is the further interesting possibility that this particular cell could be made reversible, although it is not fully reversible yet; this should be a great advantage on any vehicle which has to start and stop repeatedly.

It must be admitted that gases are intrinsically difficult to store because they require heavy and bulky gas cylinders; it is tempting to consider storing them as liquids at a low temperature, and in this respect oxygen is fairly easy nowadays. But hydrogen

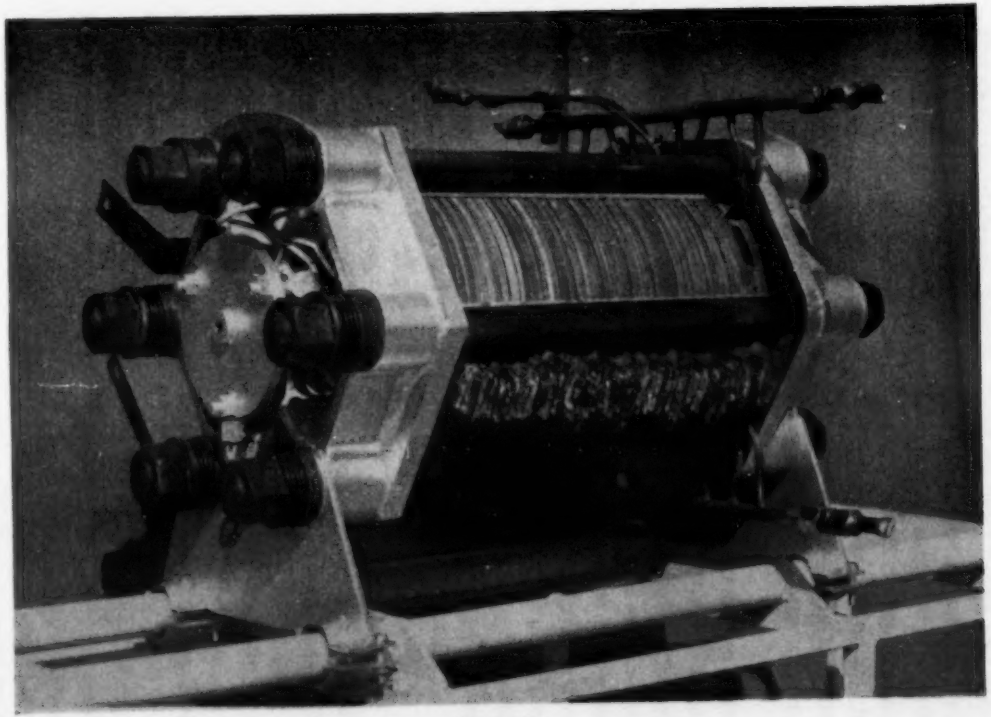


PLATE I

is much more difficult, and although liquid hydrogen is made in quantities as great as 7 tons per day in the United States for use in rockets, it is still rather expensive. So, in the meantime anyway, we are driven back to gas cylinders.

But the advantages of silence, freedom from fumes and vibration, and very few moving parts, should not be forgotten, and in certain special applications could be important. And it is well known that the torque characteristics of a direct current motor are far better than those of an internal combustion engine which has to rely on a clutch and gearbox for starting. It seems that the hydrogen/oxygen cell is essentially a high performance device, and therefore inherently suitable for traction.

One further point is that as more nuclear power stations are built, it will become even more important to look for some method of storing electricity; it is well known that the main proportion of the cost of electricity produced in this way is due to the capital cost of the plant rather than the amount of nuclear fuel used, so little is saved by shutting them down during time of light load. The present suggestion is that the electrolysers should be kept running at all times, except during the peak load period, and that the gas produced should be used for driving some of our road and rail vehicles as and when required.

Practical Demonstrations

It is hardly necessary to discuss applications for fuel cells, as these are fairly obvious if all the technical difficulties can be overcome, and the cost is not too great. The application for a cell consuming either natural gas or liquid hydrocarbons, and air, would be enormous, both for static and mobile plant, and the great oil companies have already started research work on the problem.

What practical demonstrations of fuel cells have already taken place? First, a battery of hydrogen/oxygen cells developing 1 kW was demonstrated in the United States about two years ago, as a power unit for a mobile radar set used by the U.S. army; it is known as the Silent Sentry, and in this case silence was its great virtue.

Secondly, a demonstration took place at Cambridge in August 1959 of the high pressure hydrogen/oxygen cell, in which a 40

cell battery was shown operating a small circular saw, providing power for arc-welding, and operating a fork-lift truck. The maximum power was about 6 kW.

Thirdly a demonstration was given in the United States in October 1959 of a farm tractor driven by a battery of fuel cells supplied with propane and other gases (probably hydrogen) and oxygen. It has 1008 cells in series and works at quite a low temperature; no details are given of the construction of the cells, but the electrodes must be very active catalytically to be able to make use of propane at a low temperature. 15kW. is developed and this is the first time that a vehicle has been demonstrated propelled by a fuel cell battery mounted on it. This is a great achievment, though the makers are careful to add that it is still a research vehicle.

Conclusion

Why is it that there is so much interest in the United States, and more recently in Germany, in fuel cells, and there is still so little here in Britain, though this was where most of the original work was done? Part of the great effort in the United States is no doubt Government sponsored, as there are certain military applications where fuel cells would be very valuable; and there is the vast satellite and space vehicle programme, where batteries are used extensively for providing auxiliary power. But this is not the whole story, as some large companies are putting their own money too into fuel cell research. It seems that the explanation is that the idea has "caught on" over there, whereas here it has not, as yet; and the money which American firms are prepared to set aside for research and development are in any case quite phenomenal, even on comparatively speculative devices such as fuel cells.

It is of course known that the world reserves of coal, oil and natural gas are very great, but we are using them up faster now than ever before; the fuel reserves in Great Britain are not great, in comparison, and we have to import practically all our oil. Surely attention should be given to any device which might show an economy in the use of fuel. The purpose of the vast atomic energy scheme was partly to help to conserve our dwindling coal supplies; if a small part of the effort devoted to atomic

energy could be given to a study of fuel cells in all their possible forms, we should surely obtain an answer within a very few years.

EXHIBITS IN THE LIBRARY

(*a*) Specimens of fuel cell electrodes and a model showing their manufacture; photographs and diagrams of the Bacon Fuel Cell, arranged by *Mr. F. T. Bacon.*

(*b*) Demonstration model of a 3½ litre oxygen converter; 20 litre liquid oxygen converter; a liquid hydrogen storage vessel, lent by the *British Oxygen Co., Ltd.*

(*c*) Early experimental turbine constructed c. 1889 by Sir Charles Parsons, lent by *Professor J. F. Baker, Engineering Department, University of Cambridge.*

(*d*) Three early generators, from the *Royal Institution Collection.*

SOME EPISODES IN DARWIN'S VOYAGE ON THE "BEAGLE"

By SIR CHARLES DARWIN,
K.B.E., M.C., M.A., Sc.D., F.R.S.

Weekly Evening Meeting, Friday 4th March, 1960

A. G. Gaydon, D.Sc., F.R.S.
Vice-President, in the Chair

THE SUBJECT of Darwin as a traveller can only refer to the celebrated Voyage of the *Beagle*, since to all intents apart from this he never travelled at all. For example in all his life he only once set foot on the continent of Europe, when as a youth he went as far as Paris with some cousins. The story of the *Beagle* has been often told, but the emphasis has usually been on the scientific developments to which it led. Here the proportions will be different, for the journey itself will be the central interest, and I shall describe some of the tours he made by sea and by land, in plains and on mountains, with hardly a reference to their scientific results.

In compiling my account of the voyage, I have drawn largely on the volumes about it written by Captain Fitzroy. As to the "Naturalist's Voyage" itself I have used Lady Barlow's book on it which was published in 1933. This was compiled from the actual diaries of the voyage, whereas in the original edition, published by Darwin in 1839, there were supplements drawing scientific conclusions which were made later after he had got home and could examine the collections he had sent back. In 1945 she published the actual note-books which he had compiled day by day, and these have also been useful. My main sources have therefore been Fitzroy's volumes and Lady Barlow's two books.

The famous voyage was not in fact the first tour of duty of the *Beagle* in South America. In 1826 the ships *Adventure* and *Beagle* had made a general survey of the coasts of the southern parts of the continent. The commander of the *Beagle* died in 1828 and he was succeeded by Robert Fitzroy, who was later to be in command also during the second voyage. Later again it was he who wrote two of the volumes recounting both these voyages.

One only has to read the Journal to realise that Fitzroy was a most remarkable man. He was the grandson of one of the Dukes of Grafton and on his mother's side he was a nephew of the great Lord Castlereagh. He was obviously highly expert as a navigator as well as a good commander and a very good seaman. But he added to all these essential qualities a further one, in that he was a good writer, so that his descriptions at once come alive to the reader in a way that the previous accounts had not.

A few events of the first voyage had their effects on the second. One was the discovery in Tierra del Fuego, not far north of Cape Horn, of a channel running nearly straight east and west for a hundred miles. It had been quite unknown, and they had not the time to explore it properly, and the Beagle Channel obviously called for further survey. For much of the way this channel is in fact now the frontier between Chile and Argentina.

During their time in Tierra del Fuego there had been much difficulty because the crew could not understand the natives' language. To remedy this Fitzroy persuaded three Fuegians to come on board to serve as interpreters, and with their full good will he brought them back to England so as to educate them, with a view to the later foundation of a mission station out there. One was a man whom they called York Minster, naming him after a mountain near which he had joined them, the second was a girl whom they called Fuegia Basket, and the third a boy they called Jemmy Button. The re-establishment of the three in Tierra del Fuego was one of the important tasks for the second journey.

Furthermore Fitzroy was much impressed by the opportunities which were being neglected, because the naval surveyors were quite ignorant of geology, and he resolved that in any second voyage he would try to remedy this by inviting a naturalist to join the ship. It was this post that was taken by Darwin, who when the two men first met was only 22 years old, while Fitzroy himself was only 26.

The *Beagle* returned to England in 1830, and in the summer of 1831 she was recommissioned to complete her survey, again under the command of Fitzroy. Her burden was only 240 tons, and the crowding was quite formidable, since there were 76 people on board. In addition to the ordinary crew and the

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FIG. 1.

marines, there were the specialist surveyors. Then there was Darwin, and also an artist Earle engaged for the voyage, though he was later replaced by another and in fact a rather better artist called Martens. Finally there were the three Fuegians, and a missionary Matthews who had volunteered to go and start the station in Tierra del Fuego.

Darwin messed with Fitzroy, but he slept in a cabin with two junior officers, Stokes and King, and the space was so cramped that a drawer had to be removed from a cupboard in order to sling his hammock. For the purpose of geology he took a hand lens, microscope, blow-pipe equipment, goniometer and a magnet. He had pistols and guns for shooting game, and a small carefully selected library of books, which included Humboldt's Travels, the first volume of Lyell's 'Geology', which had only just been published, and Milton's poems.

The *Beagle* was charged with the duties of completing the survey of the southern part of South America on both east and west sides, and she was to end by a circumnavigation for the determination of longitudes. There was also the obligation of taking the Fuegians home and setting up the mission station. For the longitudes the *Beagle* carried among other equipment a set of 26 chronometers and about a dozen still remained in working order at the end of the five years' voyage. It is interesting to note that at the end of this very long period the closing error for circumnavigation was only 32 seconds of time.

The survey ships of those days had acquired a bad reputation in naval circles for the health of their crews, but this reputation was not borne out during the second voyage. Allowing for the fact that much of the time was spent in the tropics, their health was excellent. It would seem also to have been a happy ship. Darwin must have proved himself a good mess-mate, for he maintained touch with several of the officers for years afterwards, as he also did with Covington, the man who acted as his servant for much of the voyage. The relations of anyone on board a ship with the captain are likely to be rather more difficult on account of his autocratic position. Aside from this, to share all meals with anyone continuously for five years would be trying, and with a man of Fitzroy's strong character there might be grave danger of a complete break-down. They did have two or three

quarrels, but they were soon reconciled again each time. However, Fitzroy's narrow fundamentalist religious views were not to be reconciled with the Evolutionary Theory, and I believe that though in later years they occasionally met, it was judged too dangerous ever to continue the intimate acquaintance.

The *Beagle* was ready to start from Plymouth in November 1831, but contrary winds drove her back several times, and she only finally left these shores on 27th December. In crossing the Bay of Biscay Darwin had his first experiences of seasickness, from which he suffered acutely during the whole voyage whenever the weather became at all stormy.

After calling at the Cape Verde Islands and St. Paul's Rocks on the equator in mid Atlantic, the *Beagle* arrived in Brazil, and stayed some time at Bahia. Here for the first time Darwin saw the wonders of a tropical forest, and I think for the rest of his life he perhaps counted this as the most outstanding experience he ever had. "The delight one experiences in such times bewilders the mind; if the eye attempts to follow the flight of a gaudy butterfly, it is arrested by some strange tree or fruit; if watching an insect, one forgets it in the stranger flower it is crawling over; if turning to admire the splendour of the scenery, the individual character of the foreground fixes the attention. The mind is a chaos of delight out of which a world of future and more quiet pleasure will arise." In the whole course of the voyage there are only two other things that made such a tremendous impression. One was the first sight of a primitive Fuegian savage, and the other was a view from a pass over the Cordillera near Santiago de Chile.

From Bahia they moved on to Rio and then to Montevideo which was to be their base for the next two years for the survey work on the east coast. The ship was much of the time engaged in detailed surveys of rather uninteresting coasts, and during these times Darwin was free to make tours inland. He made a number of journeys, some of them quite dangerous and certainly adventurous, but I can only give an account of a few of the more salient events in this period.

Their first tour was by ship to Bahia Blanca, where their reception was embarrassing, because the *Beagle* was the first warship ever to enter there, and the Governor suspected they

were going to annex the country. His suspicions were much increased when he was told that Mr. Darwin was "un naturalista", and when it was explained that this meant "a man that knows everything", his anxiety was increased further. However, later on papers came from Buenos Ayres verifying their harmless character, and they were accepted and well treated. Darwin discovered some very interesting fossil beds containing bones of the great megatherium.

In November they returned north to the river Plate, and this time they visited Buenos Ayres. He records that there were many English shops there where one could buy useful things. In his notebook there are lists of things to be bought, which include "Bramah pens, notebooks, watch mended, great teeth" (I do not know what the last means—perhaps fossils). There is also a note of the beauty of the Spanish ladies there, whose appearance, as he tells his sisters in a letter, much outshone the English ladies' at home.

The next voyage was to Tierra del Fuego, for the survey of the Beagle Channel, and also in order to set up the mission. This was in high summer, February 1833, but they encountered very bad storms. In the end they set up the mission at a place called Woolya, near the Channel and in Jemmy Button's country. York and Fuegia were now married, and they agreed to settle there too though it was not their own country. They were soon joined by Jemmy's family, but also unfortunately by many other natives. These stole everything they could of the equipment, and constantly trampled on the gardens that had been planted with peas and potatoes. It was very doubtful if it would be safe to leave Matthews alone with the savages, but it was decided to give the matter a short trial. This trial was possible because one of the objects of the cruise was the survey of the Beagle Channel and beyond, and this was to be done in two boats. Including Darwin they set off westwards from Woolya, through the various sounds right beyond the end of the Beagle Channel. One of these was named Darwin Sound by Fitzroy, who also gave his name to Mt. Darwin, a mountain slightly northwards, thought to be only very little lower than the great Mt. Sarmiento. It was a very rough life—most of the time they were wet through —camping in small tents anywhere where they could find a

secure place for the boats, and which was not, as many of such places were, a swamp. Also they had to be well away from the thieving natives.

They had one near disaster. The boats were safely up on the beach at a little distance from the encampment, in a bay near a place where glaciers from Mt. Darwin came right down to sea level. Suddenly they heard a mighty crash, and a whole wall of ice fell off into the water. There were continual echoes from all the mountains round, but to their horror they saw a great rolling wave advancing towards them which would have destroyed the two boats. The most active members of the party dashed off to secure the boats, and they were successfully hauled up out of reach of the second and third rollers without damage. As Fitzroy writes, "Had not Mr. Darwin, and two or three of the men, run to them instantly they would have been swept away irrecoverably".

They were away on this trip for nine days, going about 300 miles in all, and when they approached Woolya again their anxiety to see Matthews's fate may be imagined. He was safe, but had had a trying time, hardly able to sleep because any relaxation meant that his things were snatched or stolen. He was also maltreated to some extent, and threatened when he refused to give things away. York and Fuegia had fared better, but Button was plundered a great deal, even by his own family. It was evident that Matthews could not stay there, so he was taken off back to the ship, and gave up the mission. The three Fuegians all decided to stay at Woolya.

Immediately after this the *Beagle* left for the Falkland Islands, but about a year later she was back in Tierra del Fuego on her way through to the west coast, and they revisited Woolya. It will be best to finish off the story of the Fuegians here, rather than in chronological order. When they got to Woolya they found the place deserted though the huts were still standing. However, not long afterwards three canoes were observed to be approaching, and it proved to be Jemmy Button and his brother Tommy, and among others a wife Jemmy had acquired. Jemmy was naked except for a bit of skin round his loins; his hair was long and matted and he was very thin. He declared he was entirely happy. He spoke as much English as ever, and he had converted

all the family to the use of many English words. Fitzroy brought him on board, gave him some clothes to wear and they sat down to a meal together, which he ate in quite a civilised manner with knife and fork.

His story was this. For some time York and Fuegia his wife seemed quite settled, though there was a suspicion because York was spending much of his time in building an exceptionally large canoe. At one time they had been set upon by a tribe of enemies, but escaped to some island and took no harm, nor were their wigwams damaged. Then later York persuaded Jemmy to go off with them, as he said, "to look at his land". They all went amicably as far as Devil's Island where the Beagle Channel forks into two branches, and there after meeting some of York's family, while Jemmy was asleep one night they robbed him of all his clothes and property and made off. I believe later on that when a mission was really established in Tierra del Fuego, Jemmy had a good deal to do with it, so that it may be felt that Fitzroy's missionary efforts were not entirely wasted.

After a short visit to the Falkland Islands the *Beagle* returned to the River Plate, and Darwin went ashore at the small town Maldonado in what is now Uruguay. Here he gave up some time to lessons in Spanish. In his later life he was almost famous for being bad at foreign languages, but I think there can be little doubt that at this time he became competent at Spanish, since for many of his journeys he was living exclusively among gauchos and seems to have had no difficulty.

In the early spring of 1833, that is August, he went on the longest and I think the most dangerous of his land tours. The *Beagle* was engaged in surveying the coast of southern Argentina, and carried him down to the Rio Negro. From there he was to go north—of course all done on horseback, with several horses to each man—across the Rio Colorado to Bahia Blanca. This would be nearly 200 miles. There he would meet the ship again and then move on 400 miles to Buenos Ayres. The whole country was engaged in warfare between the gauchos and the Indians. It is hardly an exaggeration to say it was a war of extermination, though quite a number of Indians were supporting the Spaniards. The country from Carmen de Patagones to the Colorado is semi-desert, with a good many salt-pans and very

little water anywhere. Its only inhabitants were scattered bands of guanacos, that is to say wild llamas, and ostriches, with their attendant beasts of prey, and armadillos and the usual small rodents. At the Rio Colorado they met the army that was fighting the Indians. It was under the command of General Rosas who expressed interest in Darwin's plans, and granted him an interview, which passed off with great and unsmiling dignity. He was made free to continue his journey the whole way to Buenos Ayres, being given the use of the various military posts planted along the route.

When they arrived at Bahia Blanca the *Beagle* had not yet arrived, and a tedious week was passed, though enlivened by minor excursions, in particular to the fossil beds where he had previously discovered the bones of a megatherium. After a few days to re-equip himself in the ship, he set off on the 400-mile journey to Buenos Ayres. For part of this it was arranged by General Rosas that they should be accompanied by a troop of five soldiers. They in fact had no trouble on this journey, though at one of the posts a man had been killed by the Indians only a day before, and another post had been entirely massacred only a month or so before, so that life was not exactly safe.

As the traveller goes north the country gradually gets less arid, and it ends in the comparatively fertile and populated country near the capital. For most of the way it is perfectly flat pampas, but there is one mountain standing up out of the plain, the Sierra Ventana, which is a landmark for a hundred miles round. Darwin took a day off by himself to climb this, but he discovered that the mountain-climbing muscles are very different from the horse-riding ones, so that he got too cramped and exhausted to reach the very highest of the mountain's four main peaks. They took a fortnight to reach Buenos Ayres, and there Darwin enjoyed the hospitality of an English merchant's comfortable home.

After a few days' rest he set off up the Parana to Santa Fé some 200 miles north-west. This was on horseback, but at Santa Fé he was taken ill and had to return down the river by boat. He next did a tour from Montevideo round the basin of the river Uruguay. The only notable thing about this tour was that at one place the inn-keeper asked his guide if Darwin was a

Gallego, which signified whether he would be worth murdering!

The *Beagle's* period on the east coast was now nearing its end. Apart from the second visit to Tierra del Fuego, which I have already described, there are two further incidents worth recounting. The *Beagle* was surveying the remoter southern shores of the deserts of Patagonia. They called in at Port St. Julian. The river here was quite insignificant and a party set off to walk over the desert country westwards. They were loaded with arms and the survey instruments, but they did not bring enough water and suffered terribly from thirst. In the end Fitzroy and some of the men were left behind with the arms and the rest got back to the ship, and sent out a rescue party with the much needed water-bottles. They had been without water for 17 hours. Darwin seems to have stood up to the ordeal better than any of them, though he paid for it by spending the next two days in his hammock with a high fever.

An interesting point about this incident is that in later life Darwin became almost famous for his ill health, yet during the voyage he was distinguished for his strength and vigour. On at least two occasions—this one and the one I have cited already about saving the boats in the Beagle Channel—Fitzroy distinguished him for these qualities among the whole crew. It is true that he had various sicknesses during the five years of the voyage, including a serious one later at Valparaiso, but there is little evidence that his ill-health in later life was due to the stresses of the voyage.

After this expedition there was a second visit to the Falklands, and the second visit to see Jemmy Button, that has already been told. However, in the course of her work the *Beagle* had gone aground somewhere, and slightly damaged her hull, and before going to tropical waters, infested by shipworms, Fitzroy decided to lay her up and restore the coppering of the hull. This was done at the mouth of the River Santa Cruz, still further south in Patagonia, because there was a big tide there which made it possible to beach her.

The stay here was used by Fitzroy to explore the upper reaches of this practically unknown river. Three whale-boats were fitted out, but the current was so strong that they had to be towed the whole way, the twenty or so members of the party all taking

turns at the towing. After fourteen days of this back-breaking work, they reckoned they were 140 miles in the direct line from the mouth of the river, about 245 by the river's winding course, and ultimately only 60 miles from the Pacific. Their provisions were by then nearly exhausted and everyone was foot-sore and weary, so that Fitzroy decided they should spend one day, leaving the boats and going on as far west as they could walk. Above the actual river valley it was the same flat desert as ever. The next day they got into the boats, and returned to the river's mouth. They did 85 miles the first day, which in going up had cost them six days, and arrived back at the *Beagle* in three and a half days in all.

This ended the *Beagle's* stay on the east side, and she moved over to Chile to complete the survey of the west. This part of the Voyage is somehow less exciting than that in Argentina, and it can be told more quickly. The west side of Spanish South America was in fact settled long before the east, so that it gives the impression of having been a good deal more highly developed, and the various tours that Darwin undertook are therefore less exciting. At the end of one tour he was taken very seriously ill in Valparaiso. However, he seems to have recovered completely and later he did another tour among the great mountains, over the Portillo Pass to Mendoza on the east side, and back over the Uspallata Pass to Valparaiso. Later again he took two months on a journey of four hundred miles northwards along the Chilean coastal plains, visiting mountains and mines on the way, and he rejoined the *Beagle* at Copiapo in the desert regions of northern Chile.

The outstanding event of this period was a great earthquake which destroyed the city of Concepcion. The *Beagle* went there to help in the relief work, and Darwin was much interested by the changes of sea-level caused by the earthquake. In the course of his journeys he had frequently come across beds of marine shells at great altitudes, and it was these observations that suggested to him his theory of coral reefs, in fact before he had ever seen a coral island. It was the publication of this theory, when he had fully confirmed it by observation and study, that first brought his name into the hierarchy of leading zoologists.

From Copiapo the *Beagle* went on to Lima, where Darwin did

a short tour up the mountains, and then the ship proceeded to the Galapagos Islands, which was the last part of the voyage in which she was to do detailed charting. It was here that Darwin became convinced of the principle of evolution, that species were not immutably fixed, which had been the accepted doctrine hitherto. It was observation of the peculiar species, often different from one another in adjacent islands, that convinced him of this principle.

After the Galapagos the character of the voyage changed, because its concern was no longer with the making of charts, but only with the determination of longitudes. This meant that only comparatively short stays were required at each station during the circumnavigation. They called at Tahiti, then at the Bay of Islands in New Zealand, and then at Sydney, where Darwin did a hundred-mile tour to the Blue Mountains. Next came Hobart Town in Tasmania, and then King George's Sound in south-western Australia. From there they went to Keeling Island, then across the Indian Ocean to Mauritius, and so to the Cape of Good Hope, where again Darwin did a hundred-mile tour. The *Beagle* then called at St. Helena and Ascension Island on her way to Bahia where the circle of the Earth would be completed. From there she called at Pernambuco, the Cape Verde Islands and the Azores, before finally reaching Falmouth on 2nd October 1836.

In Darwin's Diary, at its end there are a few pages given to reflections on the advantages and disadvantages of foreign travel. It is well worth reading, but I am not going to describe it. However, I found one interesting point in it that I had hardly expected. As I have already mentioned, the three things that most impressed him in the whole voyage were the tropical forest, the Fuegian savage, and the Cordillera mountains. But here he records the fact that when he recalls the memories of those five years, he finds that it is none of these that first arises in his mind. It is the plains of Patagonia, without habitations, water, trees or mountains and only a few dwarf plants.

I think that in reading the Diary one does form the impression that it was the later period spent on the east side of South America that was the central feature of the whole of this great voyage.

An expanded version of this discourse was published in the *Geographical Journal*, 1960, **126**, 129–139.

EXHIBITS IN THE LIBRARY

(*a*) The original Log of H.M.S. Beagle, lent by *The Keeper of Public Records*.

(*b*) Charts made during the voyage of H.M.S. Beagle, lent by the *Hydrographer of the Navy*.

(*c*) Darwin's microscope which he used during the voyage and photographs of imaginative paintings of scenes on the voyage from the Museum Darwinianum Moscow, lent by *Sir Charles Darwin*.

(*d*) Darwin's vasculum, lent by the *Linnean Society*.

(*e*) Photographs of places visited during the voyage, lent by *The Director, Royal Geographical Society*.

(*f*) Coloured reproductions of paintings made during the voyage, lent by *The Director, British Museum* (*Natural History*).

SCIENTIFIC TECHNIQUES IN ART AND ARCHAEOLOGY

By A. E. WERNER, M.A., M.Sc., D.Phil.
Keeper, British Museum Research Laboratory

Weekly Evening Meeting, Friday 11th March, 1960

James Lawrie,
Vice-President, in the Chair

IT was in France during the last quarter of the eighteenth century that certain chemists began to apply their specialised knowledge in the field of the fine arts. Their efforts were first directed to the discovery of new artists' pigments. Thus, in 1781 Guyton de Morveau discovered zinc white which he recommended as a new white pigment that would resist the action of sulphurous fumes in urban atmospheres which tended to darken white lead. In his plea to artists to use this pigment, despite the fact that it was more expensive than white lead, he ended his paper to the Academy of Dijon with the phrase: "*On ne marchande pas l'immortalité*".[1] In 1804 the chemist Chaptal was anxious to find a blue pigment which could be used by the Sevres porcelain factory in place of the expensive imported ultramarine. He commissioned Thenard to undertake the necessary research and in a few months he discovered the pigment cobalt blue which now bears his name.

Certain distinguished scientists in this country soon began to follow the example of their colleagues in France. In 1815 Sir Humphry Davy published his classical paper entitled *Some Experiments and Observations on the Colours used in Painting by the Ancients*[2] in which he analysed and identified pigments found at Pompeii, and in 1818 he was commissioned by the Prince Regent to examine manuscripts that had been recovered from Herculaneum in order to find a way of unrolling them without damage.[3] In 1843, Michael Faraday, when lecturing at the Royal Institution, exhibited leather-bound books from the Athenaeum Club which were in a very bad state of decay. He correctly attributed this condition to the products of combustion of coal gas and demonstrated that the moisture from a gas flame, condensed on cold metal, contained sulphuric acid. This was the earliest observation concerning the decay of leather by sul-

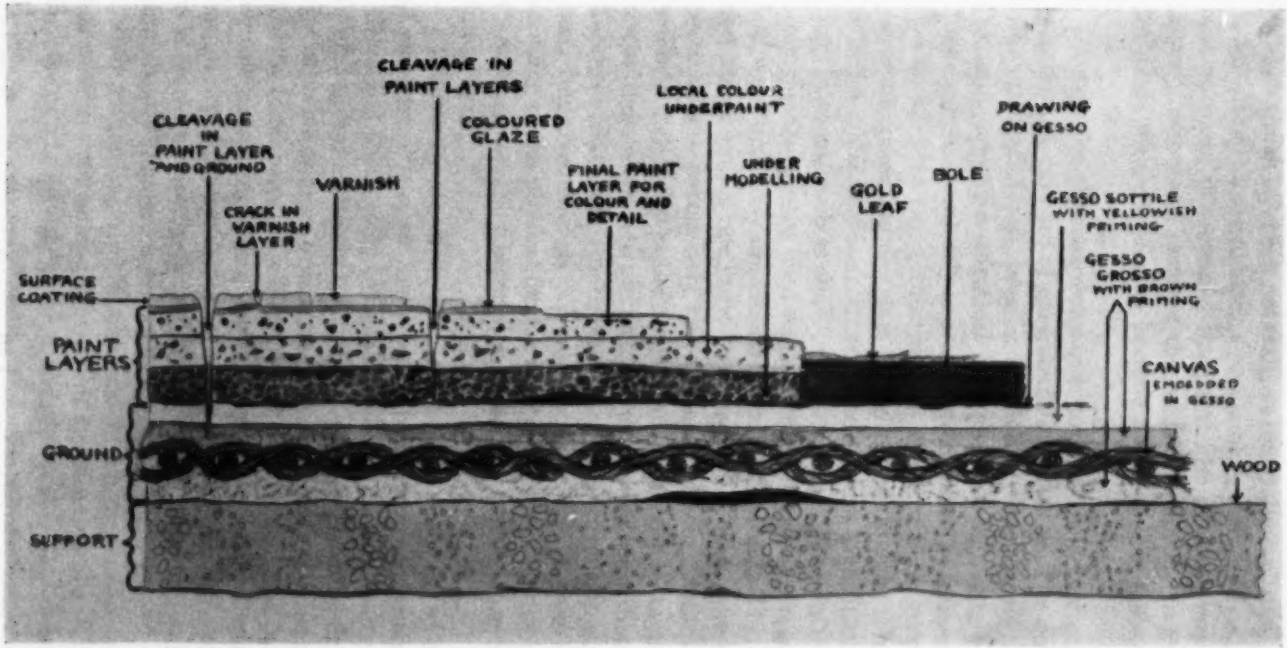
phuric acid. In 1853 Faraday served as an expert witness before the Select Committee of the House of Commons which was appointed to enquire into the methods of cleaning paintings being used at the National Gallery at that time.

These examples represent, however, isolated occasions when scientists were called upon to use their specialised knowledge. The intensive application of scientific methods in art and archaeology is on the other hand of comparatively recent origin.

The work that is carried out in museum laboratories may be considered under three aspects. The first is the application of scientific methods to the conservation of works of art and antiquities; the second is the extension of our knowledge about the materials and techniques of painters and craftsmen so as to acquire general information of value to the scholar and art historian; and, thirdly, there is the question of providing objective criteria relating to the authenticity of works of art and antiquities.

Let us consider first of all the use of scientific techniques in the examination of paintings. Normally, one regards a painting from the purely artistic point of view, but, in order to appreciate how scientific methods are employed in the examination of paintings, it is necessary to realise that, from a physical point of view, a painting is a stratified object consisting of four essential layers. These are shown diagrammatically in Plate I. In the case of early paintings, the support was usually of wood but, from about the fifteenth century onwards, canvas was used. The ground layer consisted of a white inert material in a glue medium; in Italy and Southern Europe calcined gypsum (hence the word *gesso* often used to describe this layer) was used as the white inert, but in Northern Europe it was normally chalk. Great care was taken by the Old Masters to produce a ground which would have a finished surface that would be as perfect as possible for painting upon; in the words of Cennino Cennini—the famous 15th century writer—it should be "as white as milk (*biancho chome lacte*)" and "smoothed as if it were an ivory (*pulendo si chome fusse uno avorio*)"[4]

The paint film consisted of an aggregate of pigment particles in a binding medium. In so-called tempera painting the medium was egg-yolk, but this was later replaced by various drying oils —the commonest being linseed oil.



Schematic representation of the stratified structure (vertical section) of a panel painting.

PLATE I

The varnish layer was not really an integral part of the painting. It was usually applied after a period of time and served a two-fold purpose; it protected the paint film against atmospheric contamination and restored the original brilliance to those oil paintings which tended to become rather dull in the course of time.

Among the physical techniques used in the investigation of paintings, X-rays are of paramount importance. The degree of absorption of X-rays passing through a painting will depend primarily upon the chemical nature of the pigments present. This can be conveniently expressed in terms of the mass-absorption co-efficient (μ/c), the value of which will be greater for pigments containing elements of high atomic weight. Thus, the value for white lead is about ten times greater than that for calcium pigments such as chalk or gypsum. It is fortunate that calcium pigments were used for the ground layer whereas white lead was extensively used in the actual paint layers. This means that the ground is relatively transparent to X-rays, whereas the paint layers—particularly those areas containing white lead—will be registered in radiographs. The radiographic examination of paintings is not new; in fact, shortly after Röntgen discovered X-rays in 1895, radiographs were being made of paintings. However, improvements in X-ray equipment and a true understanding of the physical factors involved in the X-raying of pictures were necessary before the technique could be used to its full advantage.[5]

Radiography can often yield information about the technique of an artist. Thus, an X-ray of the painting of *S. Catherine of Alexandria* (N.G. 168) by Raphael shows that the background (a blue sky) is relatively opaque to X-rays whereas the figure of S. Catherine is more or less transparent to X-rays. This means that the luminosity of the background has been achieved by using a paint containing a large amount of white lead, whereas the luminosity of the figure has been created by allowing the ground to serve as a white reflecting layer which shines through the thinly super-imposed layers of flesh paint.

Information can also be obtained which may assist the art-historian in determining the attribution of a painting. Thus in the case of a large altar-piece in the National Gallery originally

ascribed to Ercole Grandi (N.G. 1119) doubts were raised about the attribution. When the Madonna's head was X-rayed, the radiograph showed that the superficial image was very thinly painted and was barely visible, whereas underneath, and posed at a different angle, the original version of the Madonna's head showed up clearly and was obviously painted in a different style (Plate II). This indicated that two artists had been engaged on this altar piece. Documentary evidence showed that this painting was started by the artist Maineri, and finished by Lorenzo Costa. What we see today is Costa's version of the Madonna's head which was repainted over Maineri's version which is visible in the radiograph.

Another physical technique used in the examination of paintings is infra-red photography. Infra-red radiation has a greater penetrating power than visible light so that it can pass through the varnish and uppermost paint layers, and, if the underpaint or ground has a high reflectance coefficient around 8000 A, it is often possible to reveal *pentimenti* (i.e. alterations in composition made by the artist himself) not visible to the naked eye. One rather dramatic example of the success which can be achieved is shown in Plate IIIA. Here van Eyck's first sketch of Arnolfini's right hand which was drawn in charcoal on the white chalk ground is clearly visible beside the final painted version. The reason why the drawing shows up so well in the infra-red photograph is due to the fact that carbon absorbs infra-red radiation whereas chalk reflects it.

Difference in the infra-red reflectance of pigments can often yield information about over-painting. Thus, in a picture by a follower of van der Weyden, *The Exhumation of S. Hubert* (N.G. 783), the bishop's cope appeared to be painted in a uniform dark blue colour. However, an infra-red photograph revealed an overpainting, which appeared almost black. Subsequent chemical examination showed that the paint in this dark area was a mixture of Prussian blue and chrome yellow. These pigments absorb infra-red radiation to a greater extent than the pigment used in the original paint and hence appear dark against the rest of the cope. This overpainting had been carried out to conceal a hand belonging to the figure standing beside the bishop. When an X-ray examination showed that this hand was, in fact, not

A. Panchromatic photograph showing Costa's version of the Madonna.

B. Radiograph showing underlying version of the Madonna by Maineri.

Details from the altar-piece *Madonna and Child with Saints.*

PLATE II

badly damaged but was in a good state of preservation, this overpainting was removed and the hand once again revealed as it had been originally painted.

Ultra-violet radiation also can be used for the examination of works of art. Retouchings on paintings and repairs in ceramic or bronze objects are revealed because they show a different fluorescence from that of the background, and in the case of drawings which have faded, fluorescence under ultra-violet may render them visible. Thus, in a collection of drawings by Leonardo da Vinci in the Royal Library at Windsor Castle, there were two sheets upon which very little was visible, but under ultra-violet light, they became alive with drawings of hands (Plate IIIB) which were identified as sketches for the *Virgin of the Rocks*.[6] These sketches had been done on a pale pink paper using a soft metal (probably silver) pencil as the drawing instrument. In the course of time the traces of metal were either rubbed off or, possibly, converted into a colourless compound so that the drawing disappeared. However, there still remained enough of the metal to give the characteristic fluorescence under ultra-violet light and bring these sketches miraculously back to life.

Physical techniques give information about the structure of a painting, but chemical—or rather micro-chemical—techniques are concerned with the actual nature of the pigments and binding media used. Precise micro-chemical tests for the identification of pigments have been developed using modern organic reagents for metals in conjunction with Feigl's "spot test" techniques. Details of the method and typical examples of the reagents used in the National Gallery laboratory have been given by Miss R. J. Plesters[7]. As a natural extension of pigment identification the technique of preparing paint cross-sections has been developed. Minute fragments of paint are embedded in a suitable synthetic resin (e.g. polymethyl methacrylate or a cold-setting poly-ester) which is ground down on emery papers until the paint fragment is exposed; the layers of paint can then be examined under the microscope,[8] and information be derived about overpainting and about artists' techniques.

Recently this technique has been advanced a stage further by Dr. P. Coremans[9] who has succeeded in preparing paint cross-sections which are sufficiently thin (20—30μ) to be viewed

under the microscope in transmitted light at a high magnification. Such cross-sections permit a much more precise examination of the structure and composition of the various layers of a painting. Thus, in a fragment of blue paint from van Eyck's *The Mystic Lamb*, it was possible to recognise no less than eleven layers; of these six were authentic van Eyck and consisted of a chalk ground, an isolating layer of oil, three layers of opaque paint containing azurite and lead white in an oil medium and a translucent glaze consisting of natural ultramarine in an aqueous medium; whereas the other five consisted of three layers of varnish between which were sandwiched two layers of repaint containing the modern pigments synthetic ultramarine and Prussian blue.

When compared with the precise tests for the detection of pigments, the methods available for the identification of media were less satisfactory, and were largely based on the comparative behaviour of media towards different solvents. However, the technique of partition chromatography has been successfully applied to this problem and methods have now been developed in the National Gallery Laboratory[10] for the precise detection of the presence of resins, oil, egg-yolk and glue in paint media.

When one passes from paintings to a study of archaeological material, the problems of scientific examination and conservation are quite different. One has to deal with a wide range of objects which differ in their material make-up and are liable to have undergone profound changes whilst buried in the ground, and the problems involved are many and varied. The following examples will, however, illustrate some general principles involved in the examination and treatment of metallic antiquities.

The first example relates to a silver cup which was excavated at Enkomi in Cyprus and was dated about 1400 B.C. This was covered with green corrosion products derived from the copper present in the alloy which had been leached out while the cup was buried (Plate IVA). Preliminary examination showed the presence of gold and a black powdery substance which spectrographic analysis showed to be probably a material called *niello* (a mixture of the sulphides of silver and copper). The detection of gold and *niello* suggested the presence of a decorative inlay, and radiography confirmed that this original decoration still

A. Infra-red macrograph (X 2) from *The Marriage of Arnolfini* by Van Eyck.

B. *Study of Hands* by Leonardo da Vinci as revealed by Ultra-violet flourescence.

PLATE III

survived under the corrosion products. The problem, therefore, was to remove the incrustation and reveal the ornamentation without losing either the gold or the *niello* in the process. Experiments with *niello* prepared in the laboratory showed that this material was unaffected by hot formic acid. This reagent, therefore, was used to remove the unsightly incrustation and the original decoration was revealed, as shown in Plate IVB, in a surprisingly fresh condition[11].

The next example is instructive because it shows that, in the case of iron objects, material which at first appears most unpromising may yield interesting results. A small fragment of a Roman sword of the second century A.D. appeared to have been reduced to a mass of rust. However, radiography revealed evidence of inlays, and, with the X-ray photograph as a guide, the rust was carefully removed to reveal the inlays which had been done in a yellow alloy of copper and zinc (so-called orichalcum). On one side of the fragment there emerged a figure which was identified as the god Mars, and on the other side the Roman eagle with standards.

The conservation of archaeological material often presents problems which necessitate the development of a novel technique. Thus, about two years ago an important archaeological find was made on the site of a mediaeval church in St. Ninian's Island in the Shetlands. This consisted of 28 metal objects thought to be early Christian in origin and to date from about 800 A.D. These objects were regarded by the excavators as bronze, but examination showed that the metal was, in fact, a base silver alloy containing much copper which had mineralised during the years of burial to form a thick coating of copper corrosion products. The most interesting item in this hoard was a composite object thought to be a hanging bowl with an internal liner. This supposed liner was soon found to be a separate decorated bowl, which had been pushed into the hanging bowl, and it was easily removed and cleaned. The hanging bowl itself was of particular archaeological significance, because it is the only known surviving example of a *silver* hanging bowl to have been found in this country. Its conservation presented a problem of peculiar interest[12]. The strength of the bowl was due almost entirely to the layers of corrosion products between which egg-shell thin silver was

sandwiched, but at the same time it was considered necessary to remove this incrustation because it was unsightly and gave a false impression of the original appearance of the bowl. When cleaned, the hanging bowl was, therefore, extremely fragile so that it was necessary to devise some form of internal support to act as a permanent reinforcement. After a series of trial experiments, a cold-setting epoxy resin (Araldite Casting Resin F) was chosen because it adheres well to metal, is transparent, and sets without appreciable skrinkage. A viscous mixture of resin and hardener (together with dibutyl phthalate as plasticiser) was brushed uniformly over the inside of the bowl, which was rotated on a small turntable so as to keep the resin mixture uniformly distributed while it set. In this way it was thus possible to reinforce the bowl with a thin transparent film which gave sufficient mechanical strength so that the bowl could be handled with perfect safety.

When scientific methods are used in connection with the authenticity of antiquities, the evidence obtained may be either positive or negative. In the former case, the evidence will indicate the approximate age or the definite antiquity of the material of which the object is made, thus establishing probable authenticity. In the latter case, one seeks evidence of anachronisms in the use of materials or techniques which prove that the objects could *not* belong to the period assigned to it.

In order to appreciate how varied are the scientific methods that can be used in this field, it is of interest to mention a new technique which was developed at the Leather Industries Department of Leeds University to confirm the alleged age of the Dead Sea parchment scrolls. The first step was to take photographs with the electron microscope to show how the actual collagen fibres had undergone a characteristic degradation due to the long sojourn of the scrolls in the dry atmosphere of the caves in which they had been discovered. Then, the decrease in the shrinkage temperature of small fibres teased out from the scrolls was measured, and, by comparing the value found with that of parchments of known date, it was possible to arrive at an approximate age of about 2000 years for the Dead Sea scrolls.[13]

In the case of metal objects, a metallographic examination, both of the corrosion products and of the metal remaining

A. Cup from Enkomi showing condition as excavated.

B. Enkomi cup after treatment and restoration.

PLATE IV

beneath the corrosion layers, may provide manifestations of antiquity. It will, however, be impossible to give even an approximate age, because the rate at which a metal corrodes will be greatly influenced by its environment.

Genuine patinas are minerals that have slowly grown on the surface of the metal and under high magnification they will usually show a complex banded structure and inter-crystalline penetration into the metal, leading to replacement of metal crystals by mineral, i.e. pseudomorphism. On the other hand, false patinas which are induced by accelerated corrosion can be distinguished by the fact that they tend to be on a much smaller scale, do not usually show the banded structure nor penetrate into the metal. A metallographic study of cross-sections of patinas, particularly in the case of bronze objects, may, therefore, yield conclusive evidence either for or against antiquity.

In the case of silver objects, a study of the metal itself may be very informative. Ancient silver acquires a crystalline quality—the characteristic property that accounts for its brittleness. Fractures in the surface of the metal may look lined and decayed like old leather, and granular crystals are often visible.

In contrast to this a technical examination of a silver plate in Bactrian style (2nd to 1st century B.C.) revealed features which cast serious doubt on its authenticity. A photomicrograph of dents in the edge of the plate and scratches on the surface showed the silver to be in a ductile condition and there was no evidence of crystallisation. Moreover, when struck, the silver rang like a bell quite unlike the dead response given by highly crystallised silver. Also, the foot rim was in an almost virgin condition and showed no signs of wear; in an object of the presumed age of this plate which weighed 1128.5 grams, one would normally expect to find signs of wear visible to the naked eye. In this case none were visible even under the microscope. Another odd feature was the absence of silver chloride—the typical corrosion product of silver to be expected from the presumed environment. These findings were confirmed when the models which served for the design on the plate were traced to a manuscript of the *Fables of Bidpai* in the Yildiz Library at Istanbul.[14] Plate V shows the plate and the corresponding pages of the manuscript.

In the scientific examination of paintings of doubtful authen-

ticity, one is solely concerned either with the possible discovery of anachronisms in the use of pigments and media, or with abnormalities in technique. Three examples will show how this kind of evidence can be used to detect forgeries. In the case of a painting of a "Laughing Cavalier" attributed to Franz Hals, microchemical examination of fragments of original paint revealed the presence of no less than three pigments—synthetic ultramarine, zinc white, and cobalt blue—which were unknown in Franz Hals's time. The presence of these pigments constitutes undoubted proof that this painting could not be by the hand of Franz Hals.

The next example is the famous forgery case which shook the art world on 12th July 1945 when the Dutch artist, van Meegeren, claimed he had painted certain pictures which had been attributed to Vermeer—the most famous of which was the *Christ with the Disciples at Emmaus*[15]. Microchemical tests revealed many facts which clearly showed that these paintings were indeed fakes. Thus, the medium proved to be a modern synthetic phenol-formaldehyde resin, traces of the pigment cobalt blue were found in samples of blue paint, and the dirt in the craquelure—that network of fine cracks which is to be seen on all old paintings—proved to be ordinary Indian ink which, moreover, had in places seeped into the porous medium, thus blurring the sharp outline of the cracks, and giving them a very suspicious appearance.

It is also possible to use radiography to unearth further scientific evidence. Since potential buyers of Old Master paintings are always impressed by signs of age in the support, it is a common practice among fakers to use authentic old supports upon which to perpetrate their forgeries. In this particular case, van Meegeren bought 17th century paintings by minor Dutch artists, and scraped off as much as he could of the paint so that he had a suitable canvas upon which he could proceed to paint his pseudo-Vermeer pictures.

It is, however, very difficult to remove completely all traces of the original painting, and, therefore, when these suspected paintings were X-rayed, it was possible in all cases to detect traces of some different painting lying beneath the superficial image. In the case of one of these pseudo-Vermeers represent-

A—*FIGHT BETWEEN A LION AND A BULL*. SILVER PLATE IN BACTRIAN STYLE

B—*FIGHT BETWEEN A LION AND A BULL*; *C*. *THE HUNTER*. EACH 24.2 BY 16.8 CM. (YILDIZ LIBRARY CONSTANTINOPLE.) (REPRODUCED FROM SAKISIAN: *LA MINIATURE PERSANE*)

PLATE V

ing *The Last Supper*, the radiograph showed the distinct outline of dogs and birds. A Dutch art dealer had fortunately kept a photograph of a painting of *A Hunting Scene* by Hondius which van Meegeren had bought from him in 1938. When this photograph was compared with the above radiograph, there could be no doubt whatever that the pseudo-Vermeer *The Last Supper* was painted over what had once been the Hondius *Hunting Scene*.

The techniques mentioned so far can only be applied to detecting forgeries of Old Master paintings. When the question arises of detecting a forgery by a modern artist, anachronisms in the actual materials will obviously not apply. It is necessary instead to obtain evidence about the actual technique of the artist so that it may be compared with the technique of the suspected painting. This can often be achieved by radiography which was successfully used to unmask a number of van Gogh forgeries which came to light in 1928. When these paintings were X-rayed, a striking difference was found between the radiographs of the suspected paintings and the radiographs of genuine van Gogh paintings. The latter showed the powerful brush strokes which give van Gogh paintings their rhythm and true meaning. On the other hand, the radiographs of the forgeries showed the restless nervous brush strokes of the faker who had merely succeeded in imitating the characteristic superficial appearance of van Gogh paintings.

This account of the kind of work carried out in a scientific department attached to a museum or art gallery will show that the work is very varied, both as regards the type of problems—whether of conservation or of scientific examination—and the methods which are brought into play to solve them. The scientist is often accused of indulging his idle curiosity, and at first his intrusion into the museum and art gallery may perhaps have been viewed by the scholar with a certain amount of alarm. However, the position has now happily arisen in which there is active and intimate co-operation between the scientist and the scholar in the study of problems of mutual interest. In this field it can be justly claimed that a successful attempt has been made to bridge the gap which has sometimes been presumed to separate science and art.

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EXHIBITS IN THE LIBRARY

(*a*) A display of electrotype replicas of the Mildenhall Treasure, Sutton Hoo Treasure and the Snettisham Gold Torc; examples of moulding and deposition work carried out at the British Museum Research Laboratory; radiographs and illustrations of methods of restoration. Arranged by *Dr. A. E. Werner and the British Museum Research Laboratory.*

(*b*) The restored Mithras Head, lent by the *Guildhall Museum.*

(*c*) Two examples of faked paintings, lent by the *Courtauld Institute of Art.*

(*d*) Examples of restoration work, lent by the *Institute of Archaeology.*

A copy of a photograph of J. F. Daniell (on the left) and Faraday, taken about 1840. It is reproduced with the kind permission of Miss Rose C. Giles.

PLATE I.

MICHAEL FARADAY AND THE EVOLUTION OF THE CONCEPT OF ELECTRIC AND MAGNETIC FIELDS

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Weekly Evening Meeting, Wednesday 4th May 1960

Sir Harold Spencer Jones, K.B.E., Sc.D., F.R.S.
Secretary and Vice-President, in the Chair

ALL FORMS OF human activity have their myths which serve for a time to codify and crystallize ideas and methods into a tradition. When the historical conditions out of which these myths have sprung are altered, however, the myths themselves often linger on to challenge and bedevil future generations.

The myth of Michael Faraday, the strict experimentalist, is one of these. Its origins are, I think, fairly clear. The first half of the nineteenth century witnessed the creation of a whole host of new sciences. Chemistry, biology, electrochemistry, physiology, to mention only a few, were then erected into truly scientific disciplines. The birth of a new science is almost invariably accompanied by enormous enthusiasm. The new facts or the new way of looking at old facts which mark the beginning of a new departure stimulate waves of speculation in which the attempt is made to build overnight what generally takes decades to achieve. Many of these enthusiastic guesses may later be shown to be of real value although at the time they were ignored. A young science, however, has few criteria for the testing of general speculations. Only when the science has matured is there a "sense of the possible" which permits the critical examination of hypotheses and allows the separation of the whole grain from the straw. In the nascent stage, therefore, heavy emphasis must be put upon the foundations; no matter how beautiful or seductive a suggested superstructure may be, there will be enormous pressure to ignore it (and to discourage the activities which give rise to these speculations) and get on with the more immediate task. Faraday was midwife to a number of such new sciences. His work on electrochemistry, electrostatic induction, electromagnetism, light, and the magnetic condition of matter mark the beginning of a new tradition in these studies. Faraday's more conservative and less

gifted contemporaries recognized his genius by depicting him as a foundation builder of unsurpassed skill. Here is the familiar figure of Faraday the empiricist gently coaxing from nature the new facts upon which others could erect general theories. This evening I should like to modify this picture by adding a new dimension. You all know Faraday, the layer of empirical foundations for new sciences; I wish to introduce you to Michael Faraday, master architect, to whom new facts were the raw materials for the construction of a theoretical edifice of startling beauty and symmetry.

The concept of the field today underlies the whole picture of modern physical reality. The phrase, *physical reality* should be stressed for field theory, bristling with complicated mathematical equations and dealing with the strange properties of space seems far removed from ordinary ideas of everyday experience. It also seems out of place when the subject is Michael Faraday, self-confessed mathematical illiterate, and the epitome of self-taught common sense. Yet my purpose here is to indicate precisely how the idea of the field slowly emerged from Faraday's considerations of the nature of matter and its forces. As I shall attempt to show, the specific discoveries which earned Faraday immortality in the history of science—the laws of electrochemistry, the discovery of specific inductive capacity, the rotation of the plane of polarized light by a magnetic field, diamagnetism—were the logical deductions from an overall theory which guided him in his investigations and culminated in the concept of the field.

In a charming passage in a letter to his friend Benjamin Abbott dated August 1, 1812, he recounts the following anecdote:

> "Six or seven years ago whilst standing at the door of a gentleman's house and waiting until my knock should be answered, I thrust my head through some iron railing that separated the doorway from another and then I began to consider on which side of the rail I was. In my mind I affirmed that the side possessing my head was my station for there was my perception, my senses. I had just sufficient time to ascertain this when the door opened and my nose began bleeding by the contact of the rail and such matter as that quickly put flight to my rude metaphysics. Simple as is this instance it did more in illustrating

this case to me than all the arguments I have heard since on the subject, or all the affirmations that have been made."

This "rude metaphysics" was later refined in discussions with his friends from the City Philosophical Society and Faraday seems quite early to have accepted the main points of the view first put forward by Bishop Berkeley. In essence this philosophy rejected the idea of a separate *matter* of which the perceptible qualities of bodies were properties. Where Locke had stated that

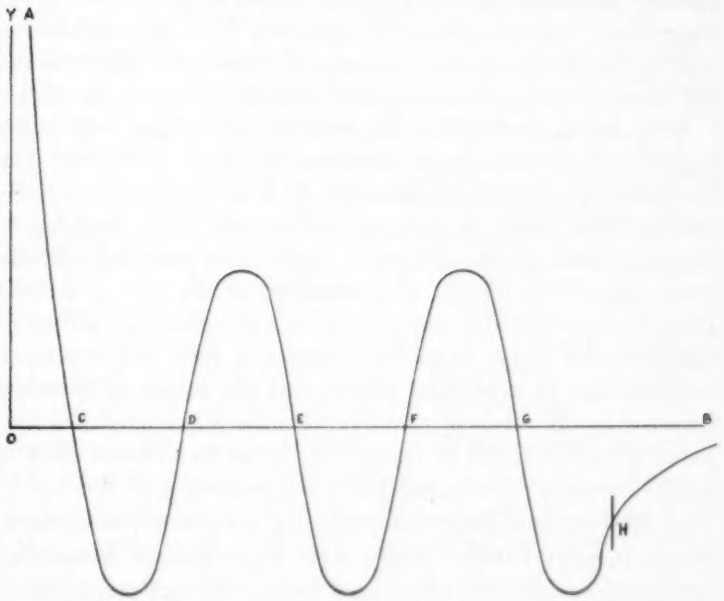

FIG. 1

there was something (matter) which remained when all perceptible qualities had been stripped away, Bishop Berkeley insisted that reality consisted solely of these perceptions and that *matter* was a mere figment of the imagination.

This philosophical point of view enabled Faraday to accept an atomic doctrine which also banished matter from the world. In the eighteenth century a Jesuit, Father Boscovich had, for purely physical reasons, rejected the "billiard ball" atoms of Newtonian science and substituted point centres of force. Figure 1 represents such an atom with its centre at O. Approaching O

along OB, one follows the hyperbola of Newton's inverse square law to H where the force becomes more steeply attractive. H marks the boundary between the macroscopic and atomic realms. From H to O, there are shells of attractive (below OB) and repulsive (above OB) force. From C, the force becomes increasingly repulsive so that no two point centres can ever coincide. Faraday himself pointed out in 1844 that this idea of an atom makes a minimum number of assumptions. We experience directly the attractive and repulsive forces of matter; we never experience "matter" without these forces. Thus, although seemingly an extremely abstract concept, this theory of matter actually corresponds most directly with our experience of the world.

Point atoms preserve all the properties of billiard balls—impenetrability, obedience to universal attraction, extension—but have advantages that billiard balls do not. In chemistry, particularly, they could be put to excellent use. The meshing of forces to yield specific and stable compounds provided a theoretical framework for the understanding of the law of definite proportions which the clumping of billiard balls could not rival. Similarly the theory explained changes of state, the regularity and stability of crystalline forms, and the origin of chemical qualities as the result of molecular form with considerable elegance. Faraday, it will be remembered, was trained as a chemist by Sir Humphry Davy and Davy was a disciple of Boscovich. With Berkeley and Boscovich providing the philosophical orientation, in 1831 Faraday began those Experimental Researches in Electricity which by 1855, were to lead him to the concept of the field.

In 1831, Faraday discovered the induction of an electric current by a moving magnet, and almost immediately after, by another current. It was this latter phenomenon which intrigued him. Why should a current be produced in the secondary when the current ceased in the primary? The particles (and by particles Faraday meant compounds of point atoms) of the secondary, he reasoned, must be in a peculiar state induced by the current in the primary. When this current ceased, the particles returned to normal, producing a deflection of the galvanometer needle. Such a state must be one of tension among the particles, the release of which created the observed current. The state of tension Fara-

day called the electrotonic state and it was to play a central role in his further investigations.

The idea that a state of tension might be induced by electrical forces among the constituent molecules of bodies provided a valuable insight into the mechanism of electrochemical decomposition. How and why the chemical components of bodies in

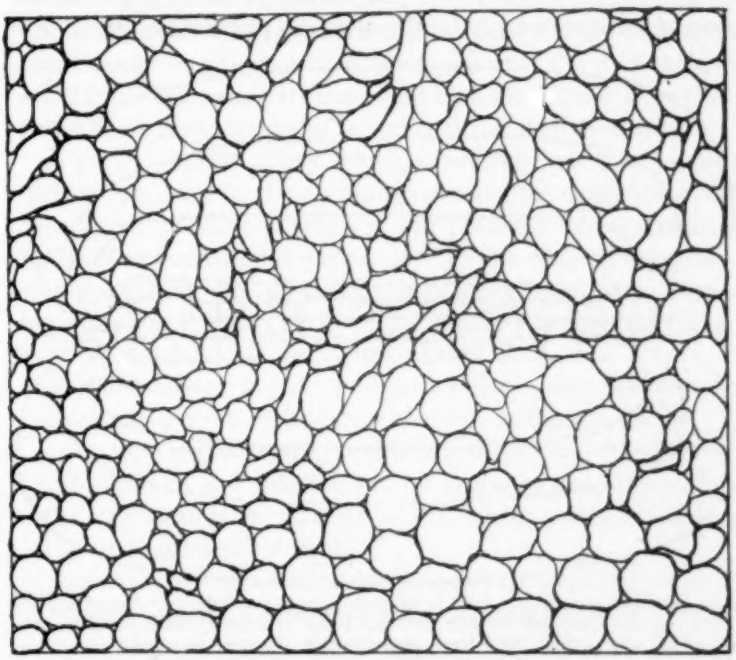

FIG. 2. A "solution" of Boscovichean particles in which the boundary lines represent the beginnings of the repulsive arch of the curve in FIG. 1. Particles, therefore, are always in contact with one another but there is no arrangement of them in a specific pattern.

solution through which an electric current could pass should be separately obtained at the electrodes without any evidence of their passage through the solution had long puzzled people. The electrotonic state offered a possible answer. As the electrical force was applied at the electrodes, the compound molecules would be strained in tension between them until a certain critical point was reached. At that point the electro-negative and electro-positive particles of the compound would break asunder and

move in opposite directions where they would immediately meet with an oppositely charged particle from the neighbouring molecule travelling in the other direction. At any given moment the constituent particles would be passing in opposite directions but tied together constantly in chemical combination, to be released only at the electrodes. (Figs. 2 and 3).

This scheme, supported by a number of clever experiments, accounted satisfactorily for the observed phenomena. But it also

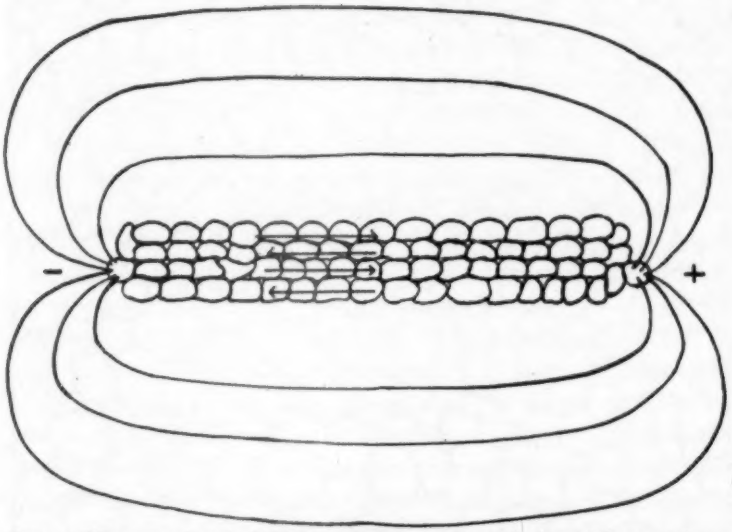

FIG. 3. When an electric field is imposed across a solution of Boscovichean particles, the particles become elongated and arrange themselves along the direction of the field. The lines pass through the centres of particles (here left out for clarity) as they align themselves in the field. The transmission of force in curved lines here becomes obvious.

had revolutionary implications. Most important of these was the denial of action at a distance which had previously been invoked to explain ionic migration. To Faraday, force was transmitted by contiguous particles and not across space. To prove this, he argued that the uniform deposition of chemical entities upon the electrodes indicated that the transmission of force was in curved lines. This could not be reconciled with action at a distance which ought to take place along straight lines. He also hinted at a new definition of an electric current (to which, however, he refused to commit himself here). The rise and fall of the

electrotonic state and the consequent transmission of force in opposite directions pleased him more than the hypothesis of one or two electric fluids which no one had yet succeeded in detecting separate from ordinary ponderable matter. The major weakness in Faraday's interpretation was the purely hypothetical existence of the electrotonic state itself. He had deduced it from phenomena but had been unable to observe it. Its rise and collapse he felt was so rapid that the state was too evanescent to detect. This evanescence was due solely to the mobility of the molecules in solution. If the same particles could be immobilized, surely the electrotonic state could still be induced and then detected.

A piece of borate of lead which, when fluid, acted as an electrolyte, was used in the attempt to observe the existence of the electrotonic condition. When it was placed in an electrostatic field and polarized light passed through it—nothing happened. The conclusion that Faraday, "the strict empiricist," drew from this was striking. He did not conclude that the electrotonic state did not exist but that,

> "notwithstanding the new and extraordinary state which must be assumed by an electrolyte, either during decomposition. . . . or in the state of tension which is assumed as preceding decomposition, and which might be supposed to be retained in the solid form of the electrolyte, still it has no power of affecting a polarized ray of light."

In *spite* of the experimental evidence, therefore, Faraday remained convinced that the electrotonic state did exist in solids. To relinquish this concept would plunge him back into the old confusion of "electric fluids" and action at a distance. With it (even though it remained hidden from sight) he could move ahead into other areas. In particular, it provided an important clue to the mechanism of electrostatic induction. In this case, as with electrolysis, the application of electric force set up a state of tension in which the contiguous particles were deformed and polarized. Discharge through a dielectric occurred when the tension grew too great for the particles to withstand and, with great release of energy, the electrotonic state collapsed. Almost incidentally Faraday showed that the breaking point ought to depend on the nature of the dielectric, i.e. that a specific inductive capacity should exist.

Again, the passage of electric force could be accounted for without the supposition of specific fluids acting mysteriously at a distance. Experiment here could decide between the two rivals. The fundamental problem to be resolved was: Did electrostatic induction occur along straight or curved lines? With infinite patience Faraday mapped the lines of inductive force and announced triumphantly, that they were curves. They must be, consequently, the result of the strain of contiguous particles.

In this masterful series of researches, Faraday had brought together a number of seemingly separate phenomena under the single law of induction. The three separate cases of metallic conduction, electrolytic conduction and disruptive discharge he had shown were reducible to the degree of strain of which the constituent particles were susceptible. Metals could take very little, so the rise and collapse of the electrotonic state was almost instantaneous; electrolytic conduction depended upon the strength of chemical affinity binding the particles together and the collapse of the electrotonic state was accompanied by ionic transfer; disruptive discharge took place when the highly strained particles, locked in their positions by the forces of solid cohesion, gave way with a snap. In each case, induction preceded conduction and conduction was viewed as the breakdown of the induced electrotonic state.

By the end of 1838, after seven years of sustained experimental and theoretical effort and with the last brick in place in his theory of electrical action, Faraday's health finally gave way. He was forced to rest and only slowly did he recover his powers of concentration and the strength to begin a new series of researches.

The new starting point was a fairly obvious one. He had shown, at least to his own satisfaction, that electrical effects were the result of the action of contiguous particles and that electrical forces were transmitted in curved lines by means of these particles. The next step was to find out if magnetic effects, so clearly involving curved lines of force, were not also dependent upon the deformation and tension of contiguous particles. Faraday's reasoning here is exactly the same as that used in the case of electrostatic induction. Since the magnetic influence could pass through non-magnetic substances (as electrostatic forces could through non-conductors) should there not be a state of magnetic

strain induced upon the particles, by which the force was transmitted? To detect this state of strain, he had recourse once again to a ray of plane polarized light passed through a piece of heavy lead glass in a strong magnetic field. This time, the plane of the light *was* rotated! Fourteen years after he had first suspected its existence, something akin to the electrotonic state had finally been detected!

Since bodies which permitted the electric force to work through them but were otherwise unaffected by electricity had been named dielectrics, Faraday christened substances through which the magnetic forces could work without being themselves magnetic, diamagnetics. Surely, however, these bodies in which a magnetically induced strain existed could not be totally indifferent to the magnetic forces. Coulomb had claimed in the 1780's that all bodies were magnetic but, except for iron and nickel, so faintly so that any effect was almost impossible to discover. By 1845 when Faraday discovered diamagnetism, most investigators had despaired of finding the effect suggested by Coulomb. With the evidence of the magnetic susceptibility of diamagnetics before him, Faraday returned to the task, using the most intense magnetic field he could find. According to Coulomb, diamagnetics should line up along the lines of magnetic force and exhibit the same, although much weaker, polarity as iron. To Faraday's surprise, diamagnetics tried to move away from the intense parts of the magnetic field and aligned themselves *across* the lines of force.

Faraday had not anticipated this result (the only effect so far which had not been a logical consequence of his theoretical views) but it did not at first perturb him. As he experimented with this new effect, observed the action of hosts of different materials in the magnetic field and attempted to account for his observations within the old framework of the strain of contiguous particles, he met with serious obstacles which were ultimately to prove insurmountable. We cannot, in the limited space available here, detail his twistings and turnings as he attempted to save the hypothesis which had served him so well. Instead I must over-simplify the tale a bit but not, I think, with any risk of distortion of the main lines of the evolution of his thought. Let us look at the next seven years (1845–52) in the light of three

questions whose answers ought to be found, according to Faraday, in terms of the strain of the constituent molecules.

1. How can the transverse alignment of diamagnetic substances be explained?

2. What kind of polarity should diamagnetics have?

3. How can the magnetic properties of gases and space be fitted within the framework of the theory of molecular strain?

At first Faraday felt that the transverse alignment of diamagnetics involved no theoretical difficulties. Diamagnetics can transmit the magnetic force only weakly; if they are placed in media which can take up a greater degree of strain, the effect would be to align the diamagnetic transversely to the magnetic lines of force and also to push it out of the field as the more highly magnetic medium displaced it. Diamagnetics, then, were not really different from magnetic bodies; they were only weaker. This being so, they should have the same *kind* of polarity as magnetics but of a much feebler strength. When tests for polarity were made, however, another unforeseen result was found. Diamagnetics had *no* polarity. If finely divided bismuth were sprinkled upon a sheet of paper under which a magnet was placed, the only effect was the repulsion of the bismuth particles from the magnetic pole; there was no mutual effect of the bismuth particles upon one another. Nor, with other tests could any polarity be detected.

Another difficulty was encountered when empty space was the medium. Iron pointed axially and bismuth pointed transversally in a vacuum. Boscovichean point-atoms, let it be noted, were infinite in extent since the force of attraction extended to infinity so that the alignment of the iron might still be reduced to the strain of "contiguous" particles. But the differential action required for the transverse alignment of a diamagnetic could not be accounted for since it involved an increase in longitudinal forces as these forces were diluted by distance—a clear contradiction.

Finally, the behaviour of gases was irreconcilable with the molecular hypothesis. Oxygen is magnetic; according to the theory of molecular strain, the oxygen molecules ought to be deformed and strained along the lines of force and the volume should decrease. Similarly, the molecules of a diamagnetic gas

should be repelled by the field with a consequent expansion of volume. Using extremely sensitive gauges, Faraday sought to find these effects and failed.

For seven years, he came back again and again to these problems trying somehow to preserve the conjecture which had served him so well. Those who insist that Faraday was a strict experimentalist who, at best, devised *ad hoc* hypotheses to aid him in specific researches and quickly discarded them once the results were forthcoming, should read his laboratory journal for these years to see the hold that theory had over him.

Gradually, however, he recognized that the facts could not be forced into his hypothesis and he quietly abandoned it as it applied to magnetism and diamagnetism. In 1852, he published a remarkable paper in the *Philosophical Magazine* entitled "On the physical Character of the Lines of Magnetic Force". The development of the ideas contained therein may be traced back to his discovery of diamagnetism, but they are here presented in all their fulness. For many years he had spoken of lines of force and, at least in his own mind, had meant the lines of molecular strain. We have, indeed, followed this idea from electrochemistry through electrostatic induction to the discovery of diamagnetism. By 1852, however, the physical basis of the strain had been eliminated. What Faraday would not eliminate, could not eliminate, because it presented itself so obviously to his eyes and understanding, were the lines of force themselves. That they existed independently of their means of detection—i.e. iron filings or a wire cutting them to generate a current—he felt must be admitted; that the action was not simply at a distance was indicated by their curved form. But he recognized the lack of a material carrier of the force.

> "I cannot conceive curved lines of force without the conductions of a physical existence in that intermediate space. If they exist, it is not by a succession of particles, as in the case of static electric induction but by the condition of space free from such material particles."

What a strange thing we now have—a strain with nothing to be strained! But wait, there is always that Aladdin's genie of the 19th century—the ether—to be brought in to solve all difficulties. Will not all difficulties disappear if space be filled by a subtle

etherial fluid capable of being strained by electric, magnetic and gravitational forces? Faraday does say that a line of force

> "may be a vibration of the hypothetical aether, or a state or tension of that aether equivalent to either a dynamic or a static conduction."

But he also goes on to point out that

> "it may be some other state" difficult to conceive.

It may be that Faraday simply suspended his judgment over the physical basis of the strain. I cannot prove that he did not but there is some very tenuous evidence to suggest that he saw these lines in a quite definite manner.

In January 1855, John Tyndall noted in his diary:

> "Heard Faraday lecture. . . . Some strange views of force—I think he deceives himself by attributing an objective existence to his mental images."

Let us go back to the boy with his head stuck through the iron railings of a fence and asking on which side reality lay. Let us see the man accepting Berkeley and Boscovich and who would freely (after exhaustive empirical investigation) accept the "objective existence" of his mental images. What would he have replied had he been asked, "what is strained in the lines of force if they can exist in space?" I think he would have said, "space itself." Nor should this really come as a surprise. What, after all, are the Boscovichean atoms but forces (i.e. strains of some kind) in space. Or, to put it another way, to ask for a physical sub-stratum to be strained is equivalent to the demand of a material sub-stratum of force. Faraday had rejected the one; I think he saw no over-riding reason not to reject the other.

What then was the field? I submit Faraday saw it as a strain in space. Matter, too, was a strain in space but it differed from the magnetic, gravitational and electric field in that it was radial (or polar), while the field was linear. The interaction of these two basic strains provided the fundamental and universal laws of the universe.

I cannot end without attempting to explain why Faraday did not come out bluntly and say that the field was a strain in space. The reason is, I feel, very simple; he knew people would think him either mad or senile (as Tyndall hints). The incredulity which greeted Einstein's statement of much the same thing, some

fifty years later after the existence of the ether had been conclusively disproved, can serve as a rough measure of what Faraday would have faced. What Faraday left were the hints from which modern field theory has been constructed. To his contemporaries, the hints were the vaporings of an extraordinary mind which seemed to get lost in areas beyond the competence of a strict empiricist. It was more comforting to entomb him in a myth than to follow his ideas to the revolutionary conclusion which is modern field theory.

Note on documentary sources

There are a number of sources, hitherto unknown, which deserve special mention. Of crucial importance are the manuscripts at the Royal Institution and the Institution of Electrical Engineers which enable us to see the early influence of Boscovich upon Faraday. Davy, in his Common-Place Book for the years 1814–16 (mss. at R. I.), revealed his own conversion to the theory of immaterial atoms and this influence upon Faraday is paramount. In the lectures which he gave to the City Philosophical Society, in 1816–19, (I. E. E.) Faraday discussed Boscovich's ideas rather generally and revealed his clear knowledge of them.

The question of the role of the ideas of Berkeley is, unfortunately, less precisely answered. The letter to Abbott which I have cited (owned by Mr. Roger Warner, Burford, Oxon. and cited with his permission) reveals Faraday's early interest in problems of epistemology to which Berkeley had already provided answers. The manuscript book of essays, kept by Faraday and a number of his friends from the City Philosophical Society (R. I.), shows that Berkeley's works were well-known and discussed there. Sir William Rowan Hamilton, a disciple of both Boscovich and Berkeley, in 1834 mentioned that Faraday agreed with him on these matters. This evidence, though indirect, appears sufficient to me to permit the suggestion that Faraday could view a strain in space without demanding a material substratum to be strained. I do not wish to suggest that Faraday accepted Berkeley's explaining *away* of matter and of the real world.

The Royal Institution has Faraday's own annotated copies of his papers. The course of his thought can only be understood in the light of this source for Faraday often explains himself in his

notes. Many of his hints about the nature of the field are to be found here and I have drawn heavily upon these volumes.

In his correspondence Faraday also sometimes explained his views more clearly than he had done in his published papers. Somewhere between one and two thousand letters have recently been turned up in all parts of the world and I have used those which were relevant to my subject to aid my interpretation of the published papers.

EXHIBITS IN THE LIBRARY

A display of Faraday's manuscripts including his Diary, Lecture note-books, letters and photographs of Faraday taken in the 1860's; his large electro-magnetic ring and Schmidt magnet; from the *Royal Institution's Collections*. Faraday's Common Place Book and letters, lent by the *Institution of Electrical Engineers*.

ARE THE LAWS OF NATURE SYMMETRICAL?

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Weekly Evening Meeting, Wednesday 11th May, 1960

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Treasurer and Vice-President, in the Chair

MANY OBJECTS are symmetrical: not only man-made things like buildings or furniture, but also the outer shapes at least of many animals, including ourselves. Indeed if we were snails that live in asymmetric shells we should probably take no interest in symmetry; and I should not stand here to deliver this lecture.

By symmetry I shall mean mirror symmetry, exhibited by such flat figures as a heart or a fleur de lis or the letter A. There are two tests for symmetry. One is to see if a plane can be found—the plane of symmetry—which bisects the figure so that of the two halves, one is the mirror image of the other. Hence any figure together with its mirror image in an arbitrary plane constitutes a symmetrical figure. The other test is to form the mirror image of the given figure and see if the two look alike. Children might find it difficult to perform that test since they notoriously confuse d and b, or p and q! (But would they call them alike if they saw them side by side? I don't know). But apart from that the two tests are equivalent, for flat figures; though not for spatial shapes, as we shall see.

Considered as a shape in space, any flat figure is symmetrical, its own plane being the plane of symmetry. The flat shape of a glove is symmetrical, but not the glove itself, whose two sides are different. Many crystals are symmetrical, but some are not. Many of them will pass the first test—of having a plane of symmetry—and it is easy to prove that they then also pass the second test, of being 'congruent' to their mirror image (Fig. 1). But the converse is not true: there are shapes that are congruent to their mirror images but that have no plane of symmetry. This is of course well known to crystallographers, but seems surprising when you first encounter it. Actually we know much more complex forms of symmetry, with several planes of symmetry; but

today we are concerned only with the basic difference between symmetrical and asymmetrical shapes.

The important point is that the internal measurements of any shape are not changed when it is mirrored. Hence for any asymmetrical shape there exist two forms, say a right-handed and a left-handed one, and the internal measurements are the same for the two. For instance, two helices may be drawn on cylinders of the same size, and at the same pitch, and yet be different. One is related to our right hand as the other is to our left hand, and so a convention for naming them has come about; but this can be used only by beings who know what we mean by right and left.

So geometry gives no preference to any shape over its mirror

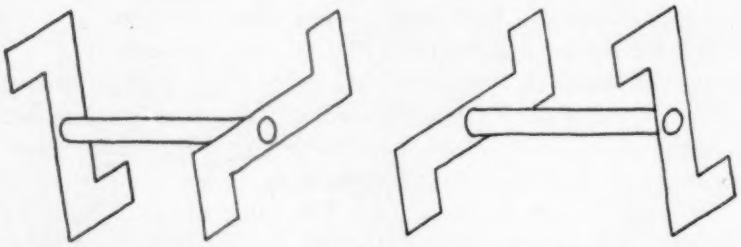


FIG. 1. These two shapes are identical (congruent) as can be seen by turning one by 90° about its rod, and are also mirror images of each other; yet each has no mirror plane.

image. Does physics? To put it more precisely; any set of geometrical measurements, carried out on a given shape, will give the same results if carried out on its image. Is the same still true if we extend it from geometrical measurements—of lengths and angles—to physical measurements, say of speeds or forces or temperatures? Would any experimental arrangement give the same result as its mirror image?

The fundamental laws of Newton on which mechanics is based certainly make no distinction between right and left. A weight hung on a string can be made to swing in a circle, and the time for a turn is the same whether it swings clockwise or anticlockwise. Actually there is a slight difference because the Earth is turning; this can be eliminated by doing the experiment on the equator, or by just correcting for it. Even then there may be a

difference because the string is twisted; so we should strictly use two weights hung by strings which are twisted the opposite way! Anyhow, if all such trivial errors are avoided the direction of swing makes no difference.

The passage of polarized light through a sugar solution seems to be different. In the absence of the solution, minimum light is obtained with the two Nicol prisms crossed; but with the solution in the light path, the second prism must be turned to the left in order to restore darkness. I turn the prism back and replace the apparatus by its mirror image: this I can do without doing anything because the apparatus, being completely symmetrical, is identical with its mirror image. Performing now the mirror experiment, I turn the prism to the right: but behold, the light gets stronger instead of weaker (as of course you knew it would!) Here there seems to be an experiment whose mirror image gives a different result.

But have I really mirrored the arrangement? No, I have not. It is rather like the pendulum with the twisted string; here the sugar molecules in the solution are twisted. If I really want to mirror the arrangement I must also replace the sugar molecules by others which are their mirror image; if I do that then a twist of the Nicol prism to the right will restore full brightness, and full symmetry is restored.

In the same way we can explain the apparent asymmetry of Oersted's famous experiment, which greatly worried him and his contemporaries. A compass needle above a horizontal wire and parallel to it gets deflected when we pass a current through the wire. As before, an apparently symmetrical arrangement gives an unsymmetrical result. But again, the arrangement is not really symmetrical. The magnetism of the compass needle should be attributed, according to Ampère, to electric currents that go round it, like the arrows on the paper sleeve I now slip over the needle. Now the arrangement is no longer symmetrical: in order to convert it to its mirror image I have to turn the needle around, and then the current of course deflects it in the opposite sense, as demanded by symmetry.

I hope those few examples will make it plausible that the laws of classical physics are indeed symmetrical. Here I mean by classical those phenomena where macroscopic bodies are con-

cerned, made from very large numbers of atoms. But in this century we have learned to observe single atoms, and here a new difficulty appears. An atom passing through a layer of gas or an electron passing through a metal foil will suffer a random deflection, either to the right or to the left. Whichever it does it behaves unsymmetrically in a symmetrical situation. But what else can it do? Its only alternative would be to remain undeflected, like Buridan's ass who starved between two equal bundles of hay, obedient to the principle of symmetry. A real ass would eat one of the hay bundles at random, and nobody nowadays would worry about his unsymmetrical action. If out of 10,000 asses in that situation 6000 turned to the right and only 4000 to the left, then we might deduce that asses behave unsymmetrically; from the action of one ass nothing follows.

So in studying single atoms we must study them many times, or many of them, and analyse the results statistically. Until 1957 (with one single exception) no atomic process had been found to behave unsymmetrically, when averaged over many repetitions. But in 1956 reasons were given to suspect the radioactive beta decay of unsymmetric features, and early in 1957 a number of experiments were performed that confirmed this suspicion. Let me perform one for you.

I have here a specimen of radioactive phosphorus, kindly lent to me by the Atomic Energy Authority. It emits electrons in all directions, but if I insert it in a suitable box of half-inch perspex I can stop all electrons except those that travel upwards and pass through the top of the box. There they strike a sheet of aluminium, and some of them are deflected by a right angle and escape through a horizontal extension of the box, only to strike a lead plate placed a short way away (Fig. 2). So far the whole arrangement is symmetrical and we should expect that of the electrons that are deflected by the lead plate, equal numbers should go to the right and to the left. But the experiment shows that this is not so: about 10% more electrons are recorded on the right than on the left.

Since the rest of the arrangement is quite symmetrical the two positions of the counter represents two experimental arrangements, one the mirror image of the other; yet they give different counting rates. But before I discuss the wider impli-

cations of this I want to describe the mechanism that accounts for this result. It is easy to verify that the electrons emerge from the box in a symmetrical stream; why, then, are more of them deflected to the right than to the left? Reversing the lead plate makes no difference, so it must be some property of the electrons. Now a similar behaviour is seen with a tennis ball that has been

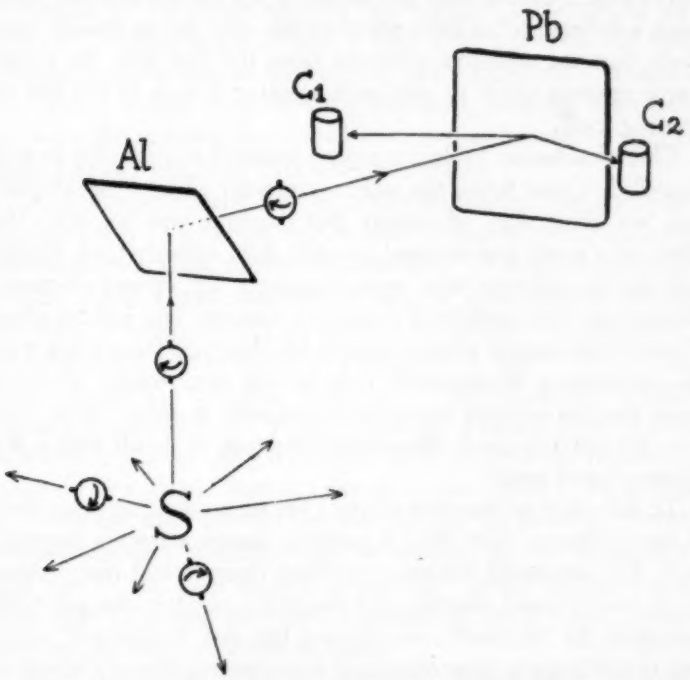


FIG. 2. Electrons from a beta-active source S tend to spin to the left about their direction of flight; that can be shown by scattering them twice, first from an aluminium foil Al and then from a lead foil Pb. The two symmetrically placed counters C_1 and C_2 then count at slightly different rates.

given a spin about an axis across its direction of flight: striking a surface normally it yet tends to go off sideways. The electrons do not, of course, bounce back from the lead plate like balls from the floor, but rather like balls from an irregular array of nail heads which represent the atomic nuclei in the lead plate. Even so, the spin does cause an asymmetry in the deflection pattern, and that asymmetry was indeed calculated by Mott as early as

1929, as soon as Dirac had formulated his mathematical theory of the electron spin.

So the asymmetry we observe indicates that the electrons emerge from the box with a tendency to spin to the right rather than to the left, like couples performing a Vienna valse. Of course they were originally travelling upwards from the radioactive source before they got deflected by the aluminium plate. Such a deflection has little effect on the spin; so we finally conclude that the asymmetry comes from the fact that the radioactive nucleus tends to give each electron a spin to the left on sending it off.

That conclusion could have been reached in 1930: for in that year C. T. Chase found the same asymmetry which I just showed you (see *Phys. Rev.* **36**, 1060). But the time was not ripe; the effect was small and seemed inexplicable; nobody took notice, and the experiment was soon forgotten. Of course electrons always spin, but usually in a random manner; and indeed when Chase's experiment was repeated with electrons from a hot wire the asymmetry disappeared (which was erroneously taken to mean that his original experiment had been in error). How then does the nucleus cause the emitted electron to fly off with a definite sense of spin?

To that kind of question physics has no answer, no more than to the question: how does a positive charge attract a negative one? The attraction between opposite charges and many other more complicated electric and magnetic phenomena are fully described by Maxwell's equations; but not 'explained', since that would require their reduction to something more fundamental, and no such reduction has yet been achieved (although Einstein and others have tried). In the same way the emission of electrons from radioactive nuclei is described in every detail, including the direction of spin, by a theory of which the foundations were laid by Fermi, over 25 years ago.

In its original form, Fermi's theory did not predict any preferential direction of the electron spins; in those days all physicists believed firmly in the symmetry of the laws of Nature. But it was soon clear that the emission of electrons—or beta rays as they were called—from nuclei was in a class apart from other atomic or nuclear phenomena. In quantum theory we compute

the probability of transition between an initial state and a final state by assuming a certain interaction between the two states; for those beta transitions that interaction turned out to be weaker by a factor of many millions than in other phenomena.

In the last decade or so, several other processes which go by weak interactions have been discovered: the spontaneous transformation of a pion (pi-meson) into a muon (mu-meson), or a neutral Lambda-hyperon into a pion and a proton. All those transformations happen within less than a millionth of a second, but that is a long time on a nuclear scale, and the interaction between the initial and the final state is found to be in all these cases just as weak as in beta transformations.

Of particular interest here were the K-mesons, particles about half as heavy as protons, which were found to break up sometimes into two pions, sometimes into three. This behaviour was in conflict with a well established rule of quantum mechanics: the rule of 'conservation of parity'. Originally, the parity of a number meant its property of being either odd or even. Later that concept was extended to apply, not just to numbers, but to mathematical functions. When a quantity y varies in dependence of a quantity x we call y a function of x, and we can represent a function by a graph. Now if a change in the *sign* of x has no effect on y we say the function has even parity (or briefly, is even); when it causes y to change sign as well, we say the function has odd parity (Fig. 3). The concept is easily further extended to the case when f depends on several quantitites, say x, y and z, which may represent coordinates in space.

Such functions of space are very important in quantum theory, where they are usually called wave functions, because they resemble waves in special cases. A wave function may have odd or even parity, and it is an important fact that the parity remains unchanged even if the system to which the wave function belongs breaks up (as long as it is not disturbed from outside). This 'conservation of parity' will hold as long as the laws which govern the system are symmetrical, i.e. make no difference between right and left, and this was never doubted until about 1956. About that time it became clear that the K-mesons presented a puzzle; it was shown that the system of three pions into which a K-meson can blow up has a wave function with the

opposite parity from that of two pions which can also result from the break-up of a K-meson. For a time it was thought that perhaps there were two different kinds of K-meson, having opposite parity; but as the measurements became more accurate and still no other difference between the supposed two kinds could be detected that idea became unpopular.

In October 1956, T. D. Lee and C. N. Yang (two young, Chinese-born theoreticians working in the U.S.A.) published a paper which made history and for which, two years later, they

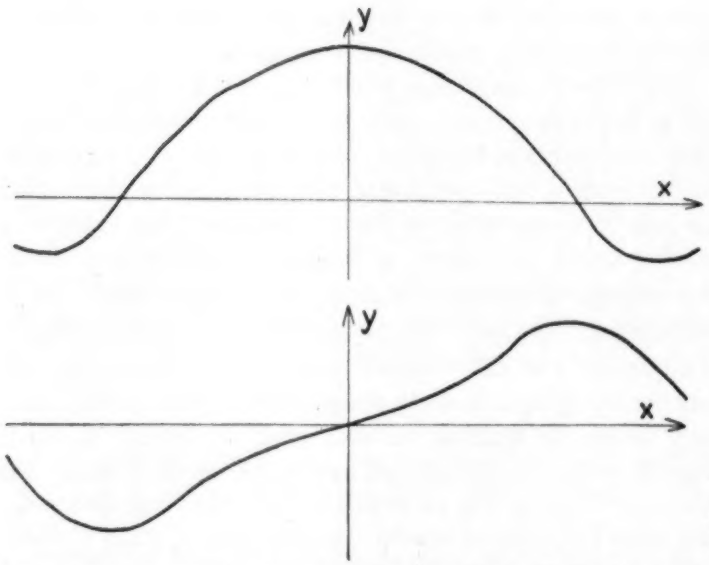


FIG. 3. Graphs representing functions of even parity (above) and odd parity (below).

received the Nobel Prize. They looked at the evidence for parity conservation in a variety of processes and found that there was no such evidence for those processes which depended on weak interactions. They proposed some tests, and within a few months they were performed, with positive results. The first tests were quite complex and needed resources found only in a few laboratories; but soon much simpler experiments were devised—like the one I just showed you—which proved the simple rule that whenever a particle that has spin gets sent out as a result of weak interaction it tends to spin in a left-handed way about its

direction of flight. You may visualize the particle like a little left-handed propeller, or that it gets fired from a barrel with left-handed rifling, but of course those are just pictures.

Does all this mean that, in her weak interactions, Nature is left-handed, and that her laws are not symmetrical? In a certain sense, yes. But we may widen the concept of symmetry. It has long been known that there is a measure of symmetry between electric charges and the opposite kind. We call them positive and negative but those are purely conventional labels (and rather unfortunately chosen since usually it is the 'negative' electrons whose movement constitutes an electric current). For a time it looked as if the positive charge was definitely associated with the heavy part of matter, the atomic nuclei, and more precisely with the protons which form part of atomic nuclei, and the negative charge with the much lighter electrons. But in 1932 positrons were discovered, which are the positive counterparts of the electrons, and negative protons were first made and observed in 1954. Ever since then it has been possible to imagine a magic mirror—let us call it a charge mirror—which would leave the shape of an object unchanged but turn all its positive charges into negative ones and vice versa. It would even affect some neutral particles: the neutron, which we can image as a small spinning magnet, would be changed into an 'anti-neutron' still spinning in the same direction, but its magnetic poles reversed. In brief, our magic mirror would turn every particle into its anti-particle; but the forces between them would not be changed thereby and the entire system would behave just as before.

But again—just as with a real mirror—what I just said is true only as long as we exclude weak interactions. I said before that any particle emitted as a result of a weak interaction tended to spin to the left about its direction of flight. But if it is an anti-particle that is emitted then it will tend to spin to the right. That can be verified experimentally: there are radioactive substances that emit positrons rather than electrons, and those positrons are indeed found to spin in the opposite direction.

So the outcome of a weak-interaction experiment is altered whether we change it to its mirror image in an ordinary mirror—which changes right to left—or in our fictitious charge mirror which changes plus to minus. But if we use both mirrors at

once then the outcome remains unchanged. To put it in a jocular way: if a physicist had steppped through the looking glass, like Alice, he would be able to tell by measuring the spin direction of electrons emitted in beta decay, following Lee and Yang; but if at the same time he had stepped into an 'anti-world' where all the particles—including those of his own body—had been transformed into anti-particles, then he could never tell the difference, not even with Drs. Anti-Lee and Anti-Yang to help him.

Does such an anti-world actually exist? We do not know yet. When a particle and its antiparticle meet they annihilate each other and their energy is converted into penetrating radiation. Such radiation is very easily detected, and very little is present on the Earth; hence antiparticles must be rare, not only on the Earth, but all through our galaxy. But we cannot exclude that other galaxies may be made from anti-matter. Our hope of finding out is based on a careful study of those cases where two galaxies collide (a slow process of interpenetration which may last a million years). If one of them were made from matter and the other from anti-matter an enormous intensity of gamma radiation would result which we might observe, directly or indirectly; but so far there has been no conclusive evidence for such radiation. So we do not know yet whether Nature as a whole is charge-symmetrical, with equal numbers of galaxies and anti-galaxies, or whether antiparticles are merely fleeting visitors to our world, created by the clash of high energy particles and annihilated again almost at once.

To sum up: before 1957 the laws of Nature were symmetrical in two separate ways which we may call space symmetry and charge symmetry. Since 1957 each of these symmetries by itself has ceased to be accurate; but they have become wedded into a vaster, more majestic symmetry, a truly royal wedding the sight of which delights the philosophical mind.

EXHIBITS IN THE LIBRARY

(*a*) Models of molecules, crystals and shells illustrating symmetry, arranged by *Professor O. R. Frisch.*

(*b*) Books illustrating shells and molluscs, from the *R.I. Library.*

LIBRARY CIRCLE MEETING

Monday, February 15, 1960

THE STRANGE BOOKS OF ATHANASIUS KIRCHER

By J. S. CHAPMAN, M.R.I.
Barrister-at-Law

H. R. Rishworth, C.B.E., F.R.C.S., M.R.I., *in the Chair*

IN the Reading Room of the Royal Institution there are many interesting books and I wish this evening to draw to your attention the works of Athanasius Kircher.

Kircher, a Jesuit Priest, was born at Geisa near Eisenach on 2nd May, 1601 and he entered his Religious Order during his seventeenth year. After a few years with the Jesuits at Paderbon he had to flee before the soldiers of the Lutheran Bishop of Halberfalt who had declared that he would hang all Jesuits.

Kircher was ordained and was sent to Speyer where he started to take an interest in strange phenomena: Speyer had then the finest library in Europe and his interest was aroused in hieroglyphics by a book containing prints of the obelisk which Pope Sixtus V had set up in Rome.

After travelling Europe from one seminary to another he settled in Rome and except for a short journey through Sicily to Malta and back when he visited Etna, Stromboli and Vesuvius, he spent the remainder of his life devoted to his books and scientific research. He died in his eightieth year having spanned the reigns of ten Popes.

Kircher had a prodigious output of books all written in latin, the content being partially fact and research, and partly fantasy. He produced during his life twenty-two volumes in folio, eleven in quarto and three octavo on such diverse subjects as theology, philosophy, universal language, archaeology, china, history, geography, magnetism, optics, acoustics, music, astronomy, medicine and magic. He was as you can imagine considered a profound student by his friends and a charlatan by his enemies. Anything odd attracted him to study and write about it and for many years his collection of fossils, antiques and apparatus was stored at the Kircher Museum in Rome.

Most of his books are profusely illustrated with his ideas and fantasies. For instance in his book on hieroglyphics, he had no true knowledge of the key to Egyptian hieroglyphics although he was certainly clever enough to make many shrewd guesses, thinking that the symbols represented ideas and it was not until Boussard in 1799 discovered the Rossetta Stone that the world learned Kircher's error.

He did however advance many ideas in medicine on contagion and in optics which certainly can be considered as a start to our modern learning. He was probably the first to use a microscope and to describe what he saw and in the case of disease he got half way to the solution of contagion but for the wrong reason. Nothing lasting was achieved by him or by his experiments and scholarship, but being an extremely good guesser he published many ideas which have since been proved to be partially correct.

I do not wish to discuss his ideas in any detail but he certainly understood much about the principles of light and his work in this field is considerable, although he pursued little to its logical conclusion—he invented the magic lantern, or at least described it for the first time.

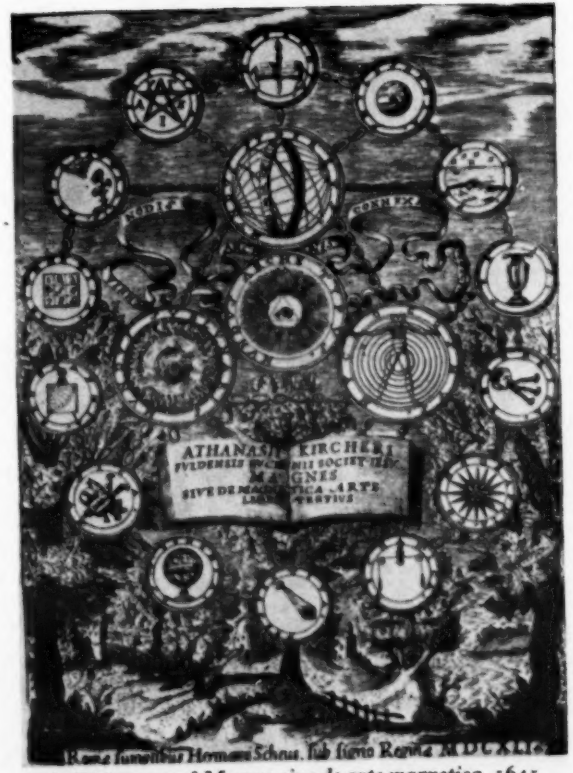
The Royal Institution possessed several of Kircher's works by 1809, when the first Library Catalogue was printed. His *Latium id est Nova et Parallela* printed in Amsterdam in 1671 by Joannem Janssonium à Waesberge is bound with *Turris Babel* printed by the same man in 1679. Both are magnificent folio books the first dealing with Roman archaeology and the second of course with the Tower of Babel with prints and plans to suit any architect. The Library also owned the *Mundus Subterraneus* —but more of this volume later.

The other books now owned by the R.I. but which I shall not deal with in detail are:—

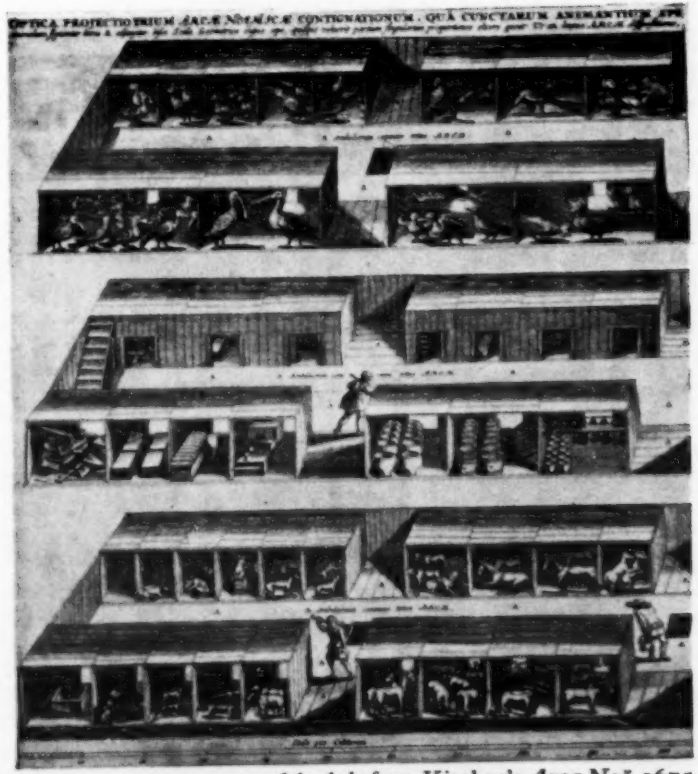
Ars Magna Sciendi in XII books printed by Waesberg in 1669.

Sphinx Mystagoga sive Diatribe Hieroglyphica printed by Waesberg in 1676—a very fine work with many fanciful illustrations of pyramids, mummies etc. hieroglyphics with interpretations and a dissertation on embalming taken almost word for word from Heroditus.

Phonurgia Nova sive Conjugium Mechanico—physicum Artis et Naturae—a small folio printed by Dreherr in 1673. This



A. Title page of *Magnes sive de arte magnetica*. 1641.



The internal arrangement of the Ark, from Kircher's *Arca Noë*. 1675.

PLATE I

book on Kircher's theory of sound and music is illustrated with many amusing plates of some terrifying instruments.

Obeliscus Pamphilius printed in Rome in 1650 was Kircher's greatest nonsense being his interpretation of the hieroglyphics of Egypt. The book is extremely learned, but after the finding of the Rossetta Stone, was found to be wrong in every aspect of Kircher's case.

Finally of the lesser books, I wish to mention the *Magnes sive de arte magnetica* of which we own two copies, one printed in 1641 (Plate I) and the other in 1654. The 1654 copy was presented to the Library by Faraday. It is not a particularly interesting book, dealing with red herrings by the shoal; it also deals with telepathy, medicine, and includes a treatise on weather cocks. It deals too with magnetism in medicine and music.

Of the three books requiring closer study I will deal first with the *Arca Noë* in three books printed by Waesberg in 1675. This book is a highly imaginative book on Noah's Ark containing hundreds of illustrations with a particularly fine frontispiece of Charles II of Spain.

The Ark and the deluge was more a subject for a divine than many of his other works, particularly as there had been and still is much controversy over the details contained in Genesis. The deluge is mentioned in five ancient books and Kircher drew on them all for his present work and there are references to Genesis, the Babylonian flood tablets of Berossus, the Indian deluge story, the Zoroastrian myth and finally the well-known Phrygian story from Ovid.

You will recall that Noah was commanded to build an Ark to save himself, family and two of every living creature to repopulate the postdiluvian earth. The details of the Ark in Genesis and the other authorities are, to say the least of it, very scanty; so Kircher, even more than usually, drew on his imagination. The Ark according to Genesis was to be three hundred cubits by fifty by thirty, and Kircher considered that, at one-and-a-half feet to the cubit, to be sufficient for its measurements the Ark would be about three thousand five hundred tons.

To discuss the three books seriatim, we find that Book 1 deals with the sin of the antediluvian world and then goes on with the technical construction of the Ark—the many illustrations show-

ing both internal and external arrangements are highly ingenious (Plate I) and the internal arrangement with the animals in situ shows the unicorns in their pens. The illustrations are however of great use as they show the clothes and carpenters' tools in use in the seventeenth century.

Finally Book I contains a fine bestiary showing the animals taken into the Ark, including unicorns, harpies and griffins. The bestiary contains an illustration of Hoopoe (Upupa Epops) rare in England but common in Italy and it is, as far as I can find, the earliest representation of this particular bird.

Book II contains the internal arrangement of the Ark, mainly by illustration with a final print of the animals going in two by two. Then the deluge and a longish treatise on buoyancy and finally a plate with the Ark floating on the surface of the water with a fine Norman Church at the bottom.

Book III shows us the recession of the waters, Noah's sacrifice to God. There are maps of the new world showing both Atlantis and Terra Australis Incognita.

Probably the finest print in this book, or for that matter in any of his books, is of the fall of man in the Garden of Eden completely surrounded by a box hedge and appropriate topiary. The Ark sits on a mountain in the top right hand corner.

Ars Magna Lucis et Umbrae printed in Rome by Scheus in 1646 is a fine book on superb paper and is a mine of information on light and colour. Its main importance is that it is the earliest book dealing with the microscope. Kircher did not claim to invent it but he says it was invented by Drebbel, and his instrument was a present from Cardinal Medici. Kircher certainly grasped the principles of light and optics and even described how a compound microscope should be made.

This book is very comprehensive where light is concerned and there is a considerable amount of accurate research. Although not universally accepted as such Kircher is attributed with the invention of the magic lantern—in any case he was the first to describe it. The book also deals with the structure of the eye and there are a number of interesting chapters on navigational instruments; these are much in advance of his time. He discusses the use of a chronometer although he doubted if one could be made. He mentions too the possibility of flying machines al-

Kircher's map of the ocean currents, from his *Murdus Subterraneus*. 1678.

PLATE II

though his ideas here were probably taken from Leonardo da Vinci.

The *Mundus Subterraneus* printed by Waesberg in 1678 and mentioned in the first catalogue is probably his best known book.

Kircher promised this work to the world after he had experienced the earthquake of Calabria in 1638. In view of his learning however there was great expectation of a fine work—in this the world was disappointed, particularly as he offended many of the learned persons of the time who believed in alchemy and the transmutation of metals.

Like all his other books, Kircher is super-extravagant with his adjectives and "admiranda et admirabilis" appears on almost anything observed or conceived to be out of the common place. In his preface he says he writes nothing which he has not himself observed or which he has not proved through men of the highest integrity, but notwithstanding this the *Mundus Subterraneus* must stand for all time as his greatest work of fiction.

The chief justification for the title of the exotic book is Kircher's hypothesis of vast underground reservoirs in Asia, Switzerland, Africa and South America from which all rivers flow. He connects the inland seas with underground channels and there are some fine maps showing the course of these imaginary streams. He proves his hypothesis by saying the Caspian and Mediterranean seas would overflow if it was not for these subterranean outlets.

He affirms in Book I that a whirlpool at the North Pole sucks the spare water in and by means of a super canal transports the water to the South Pole and there spews it out again, hence the ocean currents and he draws maps to prove his theories, the first maps of ocean currents ever produced (Plate II).

This book is full of fantastic tales of dragons (Plate III top), snakes, snow geese, serpents, etc. There are many chapters of subterranean fires, and fine illustrations of earthquakes and Etna in eruption (Plate III bottom).

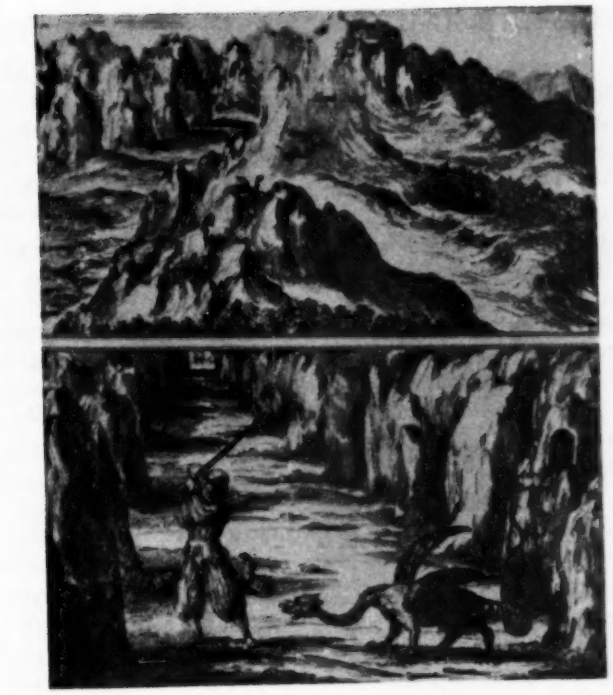
It is impossible to describe these books adequately in the short time at my disposal and I can only recommend that members should peruse them at their leisure.

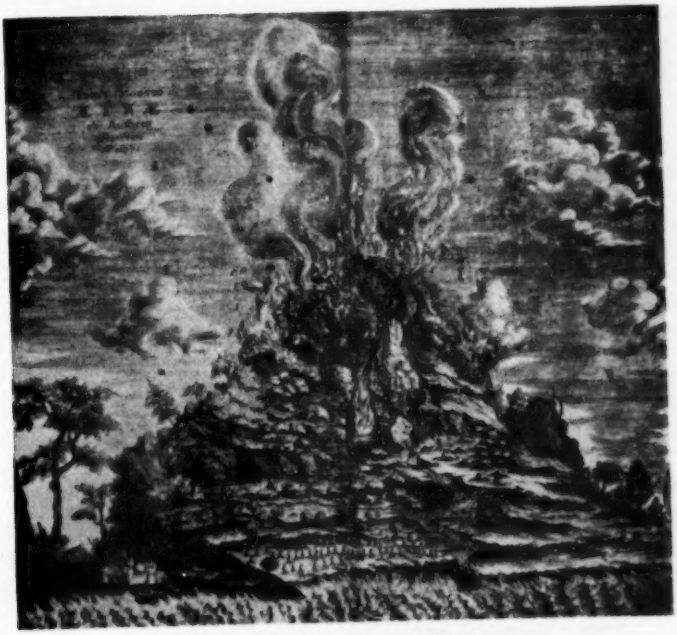
Before I finish I should like to draw your attention to the tall copy of the *Magnes* mentioned in the 1809 catalogue in which

Kircher describes and illustrates a thermascope that he had invented. Count Rumford is credited with the invention of the thermascope, and it might be that he borrowed his ideas from Kircher after idly turning the pages of this very book.

Kircher must have known that much of his work was fantasy and I can only advance the theory that the Church was disturbed at the scientific writing of Galileo and other scientists, thinking that they were proving Church doctrine to be wrong and that the Church encouraged Kircher and other Jesuits to write theories on scientific matters which would fit in with the religious doctrine of that day. As Kircher only half supported the Church, we must presume that he wrote for his own aggrandizement and was the greatest scientific charlatan of all time.

The talk was illustrated by lantern slides and a display of books by Athanasius Kircher.





Two illustrations from *Mundus Subterraneus*.

PLATE III

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Members of the Royal Institution support by their subscriptions an institution devoted to the prosecution of scientific research and to the diffusion of science and of useful knowledge. Its dual purpose of research and exposition is served by the scientific work carried on in its laboratories and by its Friday Evening Discourses and Lectures on science, literature and the arts.

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PRINTED BY OLIVER BURRIDGE AND CO. LTD., CRAWLEY, SUSSEX